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ASSESSING THE IMPACT OF CONGESTION DURING A MULTI-COUNTY EVACUATION

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THESIS

ASSESSING THE IMPACT OF CONGESTION DURING A
MULTI-COUNTY EVACUATION

by

April E. Malveo

March 2013

Thesis Advisor: Emily M. Craparo
Second Reader: David L. Alderson

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We find that a mass evacuation can more than double the clearing times of individual county evacuations. However, during both county and mass evacuations, resident routing choices significantly impact clearing times. As more residents choose suboptimal routes, clearing times are prolonged. Lastly, we find that more than 50% of residents will experience congestion at some point during the evacuation horizon. However, allowing some congestion improves evacuation clearing times by 20–36% over not congesting. Although congestion decreases vehicle travel speed by 70–80%, over 50% more residents are able to start or continue evacuating during each time epoch.

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ASSESSING THE IMPACT OF CONGESTION DURING A MULTI-COUNTY
EVACUATION

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Submitted in partial fulfillment of the
requirements for the degree of

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This thesis introduces an integer linear program called the Minimum Cost Flow with Congestion Assignment (MCF-CA) model. MCF-CA is a multi-period evacuation model that uses a novel approach called *congestion assignment* to analyze clearing times during mass evacuations. Congestion assignment discretizes the nonlinear relationship between the number of vehicles on a road segment and the maximum speed at which those vehicles can travel. MCF-CA selects among three congestion levels (none, moderate, and high) for each road segment in each time epoch. Depending on the congestion level selected, MCF-CA limits the number of vehicles that are able to traverse the road segment and uses Akçelik's Time-Dependent Speed-Flow Function (Akçelik 2003) to determine the average travel speed of the vehicles for that time period. As a result, we are able to determine approximate evacuation clearing times under nonlinear congestion effects by solving an integer linear program. We limit residents' prior knowledge of traffic conditions by implementing MCF-CA in a rolling horizon fashion and study the impact of this limited knowledge on evacuation patterns. We also model the impact of sub-optimal routing decisions on the part of residents by artificially shifting residents toward their own shortest paths rather than a "socially optimal" route.

We find that a mass evacuation can more than double the clearing times of individual county evacuations. However, during both county and mass evacuations, resident routing choices significantly impact clearing times. As more residents choose suboptimal routes, clearing times are prolonged. Lastly, we find that more than 50% of residents will experience congestion at some point during the evacuation horizon. However, allowing some congestion improves evacuation clearing times by 20–36% over not congesting. Although congestion decreases vehicle travel speed by 70–80%, over 50% more residents are able to start or continue evacuating during each time epoch.

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LIST OF ACRONYMS AND ABBREVIATIONS

FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
HCM	Highway Capacity Manual
HES	Hurricane Evacuation Study
MCF	Minimum Cost Flow
MCF-CA	Minimum Cost Flow with Congestion Assignment
NETVAC1	Network Emergency Evacuation Model
SSHWS	Saffir-Simpson Hurricane Wind Scale
TDSF	Time-Dependent Speed Flow Function
TEZ	Traffic Evacuation Zone
USACE	U.S. Army Corps of Engineers

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EXECUTIVE SUMMARY

This thesis introduces an integer linear program called the Minimum Cost Flow with Congestion Assignment (MCF-CA) model to analyze the impact of mass evacuations on clearing times, explore the impact of resident routing choice on clearing times, and assess the impact of congestion during a multi-county evacuation. MCF-CA is a multi-period evacuation model that uses a novel approach called *congestion assignment* to analyze clearing times. Congestion assignment discretizes the nonlinear relationship between the number of vehicles on a road segment and the maximum speed at which those vehicles can travel.

We model a multi-commodity transportation network involving the 216 census tracts of Mobile County, Alabama, Baldwin County, Alabama, and Escambia County, Florida. We limit residents' prior knowledge of traffic conditions by implementing MCF-CA in a rolling horizon fashion and study the impact of this limited knowledge on evacuation patterns. We also model the impact of sub-optimal routing decisions on the part of residents by artificially shifting residents toward their own shortest paths rather than a "socially optimal" route.

We find that a mass evacuation can more than double the clearing times of individual county evacuations. Exit locations, not simply the number of exits, play a significant factor in estimating clearing times. Emergency managers must sometimes encourage residents to use exits that are distant in order to ensure timely evacuation of all residents.

We find that routing choices greatly impact clearing times. We develop four scenarios that vary the percentage of residents that cooperate towards obtaining a "socially optimal" routing or do not cooperate and follow sub-optimal routing. In the base case, *Global Cooperation*, all residents cooperate to obtain optimal routes. In the second scenario, *Moderate Cooperation*, approximately 25% of residents follow their own shortest path. In the third scenario, *Low Cooperation*, approximately 75% of residents follow their own shortest path. In the fourth scenario, *No Cooperation*, 100% of residents

follow their own shortest path. *Global Cooperation* offers the most flexibility in route choices. *No Cooperation* offers no flexibility in route choices. We show that in scenarios with a higher percentage of residents following their shortest path, clearing times lengthen by as much as two to four times. This result implies that increased flexibility in route choice improves clearing time. Additionally, the more flexibility residents have in choosing their routes, the less congestion they are likely to experience. Thus, intelligent routing decisions by residents are the key to ensuring an efficient evacuation.

In the best- and worst-case scenarios, more than 50% of residents will experience congestion at some point during the evacuation horizon. However, congestion alone does not increase clearing times. In fact, if MCF-CA is restricted to disallow congestion, clearing time increases significantly. Specifically, allowing some congestion improves evacuation clearing times by 20–36%. Although congestion decreases vehicle travel speed by 70–80%, over 50% more residents are able to start or continue evacuating during each time epoch.

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I.   INTRODUCTION

In 2006, the Federal Highway Administration (FHWA) reviewed and assessed 63 Federal and State evacuation plans for catastrophic hurricanes and other events impacting the states bordering the Gulf of Mexico. The devastating destruction of Hurricane Katrina prompted a focused study on the critical issues surrounding mass evacuations. The FHWA study, "*Catastrophic Hurricane Evacuation Plan Evaluation: A Report to Congress,*" assessed the various plans in light of lessons learned about evacuation efforts employed during Hurricane Katrina (FHWA 2006). Prior to Hurricane Katrina, several mass evacuation plans existed. However, none of them were adequate for the scale of destruction that Hurricane Katrina thrust upon Louisiana, Mississippi and Alabama (FHWA 2006). Before Katrina made landfall, emergency managers ordered more than 1.2 million people to evacuate (DesRoches 2006).

The FHWA study evaluated the strengths and weaknesses of written evacuation plans in terms of how well they met existing Federal Emergency Management Agency (FEMA) planning guidelines of the National Response Framework (formerly National Response Plan) (FEMA 2008) and the State and Local Guide 101 (FEMA 1996). A specific focus of the study was the extent to which evacuation plans were coordinated with those of neighboring states and adjoining jurisdictions. The study noted that local mutual-aid agreements for joining resources and coordinating decision-making across jurisdictions did not address catastrophic events when neighboring jurisdictions would be inundated and unable to provide assistance. The study also cited inadequate real-time command and control of mass evacuations across all levels of government and across multiple states, and it recommended development of additional evacuation modeling tools to predict evacuation times and manage operations in real time (FHWA 2006).

The *Catastrophic Hurricane Evacuation Plan Evaluation* focused on the written contents of evacuation plans, not the quality of the plans in terms of effectiveness and efficiency. In 2010, the FHWA published the study "*Highway Evacuations in Selected Metropolitan Areas: Assessment of Impediment*" as a complement to its 2006 study on evacuation plans. This study assessed mass evacuation plans for high-threat metropolitan

areas to identify and evaluate deficiencies of the national highway system that could impede evacuations. The FHWA reviewed existing plans and conducted interviews with local jurisdictions, including FHWA Division staff, state and local transportation officials, and emergency managers. The expert knowledge of local authorities constituted the basis of the report's findings for each metropolitan area. Results from each area vary in the range of impediments described. However, local experts all cited congestion from insufficient capacity as the leading impediment to timely evacuation (FHWA 2010).

The two FHWA studies highlight the impact of road capacity, traffic congestion and inter-jurisdiction cooperation in the timely evacuation of large masses of people. They also highlight the need for tools to assess congestion and predict evacuation times. Effective evacuation modeling tools are essential for state and local emergency managers to test scenarios and to facilitate decision-making. Many transportation analysts have created evacuation models with the goal of accurately predicting the time required to completely evacuate residents, known as the *clearing time*. We describe four such models in Chapter II. However, none of the models focuses on the dynamic complexity of traffic congestion at the neighborhood level.

A.   CONTRIBUTIONS

This thesis introduces an integer linear program called the Minimum Cost Flow with Congestion Assignment (MCF-CA) model. MCF-CA is a multi-period evacuation model that uses a novel approach called *congestion assignment* to analyze clearing times during mass evacuations. Congestion assignment discretizes the nonlinear relationship between the number of vehicles on a road segment and the maximum speed at which those vehicles can travel. MCF-CA selects among three congestion levels (none, moderate, and high) for each road segment in each time epoch. Depending on the congestion level selected, MCF-CA limits the number of vehicles that are able to traverse the road segment and uses Akçelik's Time-Dependent Speed-Flow Function (Akçelik 2003) to determine the average travel speed of the vehicles for that time period. As a result, we are able to determine best-case evacuation clearing times under nonlinear congestion effects by solving an integer linear program. We model a multi-commodity

transportation system involving the 216 census tracts in Mobile County, Alabama, Baldwin County, Alabama, and Escambia County, Florida. We limit residents' prior knowledge of traffic conditions by implementing MCF-CA in a rolling horizon fashion. We also model the impact of sub-optimal routing decisions on the part of residents by artificially shifting residents toward their own shortest paths rather than a "socially optimal" route.

B.   SCOPE OF STUDY

This thesis conducts a meso-scopic (neighborhood-level) transportation analysis of coastal Alabama and Escambia County, Florida. We construct an evacuation road network and estimate network vehicle demand using the 2010 Census Bureau American Community Survey. We model a road network consisting primarily of freeway segments and do not consider interaction of vehicles at segment junctions. We calculate clearing times and examine residents' congestion levels under a variety of scenarios.

C.   THESIS OVERVIEW AND ORGANIZATION

Chapter II gives an overview of evacuation concepts, reviews existing evacuation models, and summarizes basic transportation terminology and traffic flow concepts. Chapter III discusses the methodology for developing the road network used in this thesis. Chapter IV introduces the MCF-CA model. Chapter V presents detailed results and analysis, and Chapter VI presents conclusions and identifies future work.

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II.   BACKGROUND AND LITERATURE REVIEW

According to a 2004 Cambridge Systematics study, since 1982 both big and small cities indicate that they have not been able to keep pace with the rising demand for transportation infrastructure (Cambridge Systematics, Inc. 2004). With a growing population more dependent on vehicle travel more than at any other time in history, U.S. highways, bridges, and roads see more congestion at all times of the day. During normal rush-hour traffic, drivers could spend as much as two hours on a 10-mile commute. Even during off-peak hours, commuters can spend close to 40 minutes for the same 10-mile drive (Cambridge Systematics, Inc. 2004).

Congestion is a complex phenomenon characterized by stop-and-go or slow-and-go traffic. Several conditions directly and indirectly influence congestion intensity, such as time of day, lane width, and the presence of car accidents and work zones. In short, bottlenecks in the road system create congestion. Bottlenecks form when:

- Vehicle arrival flow rate exceeds the capacity of a road segment,
- A queue from a prior bottleneck on the segment has not dissipated, or
- Traffic flow is affected by downstream conditions (Transportation Research Board 2010).

Regardless of the combination of influencing conditions, congestion results from having too many cars in the same place at the same time.

During mass evacuations, entire regions place simultaneous demands on transportation systems. A significant number of vehicles move across a road network in a short period of time. State and local emergency managers have emergency evacuation plans in place to help alleviate traffic congestion and ensure residents are able to evacuate in a timely manner. However, mass evacuations present conditions where overwhelming traffic congestion can lead to unsafe road conditions. Vehicle speed decreases rapidly as conditions become more congested. Consequently, travel time grows rapidly. Traffic congestion can lead to an increase in traffic accidents because of closer vehicle spacing or more stalled cars due to overheating during longer commute times (Cambridge Systematics, Inc. 2005).

This thesis builds upon and complements prior work in network flow optimization, traffic congestion analysis, and road capacity concepts. We now review the literature most relevant to this study.

A.   EVACUATION MODELS

Langford (2010) presents a space-time flow optimization model to evaluate clearing times for neighborhood-level evacuations. The model determines "best case" evacuation routes and clearing times using a minimum cost network replicated over several time periods. For the neighborhood analyzed, Langford concludes that "the presence of background traffic flow on a major evacuation road with non-evacuation traffic does not greatly impact the neighborhood evacuation; rather the overall evacuation time is more significantly impacted by the interior roads of the neighborhood" (Langford 2010).

Yuhas (2011) uses a single-commodity, multi-period minimum cost network flow model to evaluate evacuation routes and clearing times for residents of Yolo, Sacramento, San Joaquin and Stanislaus Counties of Central California. The model assumes travelers have "perfect knowledge" of road conditions before evacuation. Yuhas uses pre-defined road capacities to determine the effect of congestion on the network, and he assesses contra-flow opportunities to improve clearing times and the effect of highway inundations on clearing times. Contra-flow is the reversal of traffic flow on portions of a road to allow more flow in the opposite direction.

Fosgerau (2008) uses a bottleneck model developed by William Vickrey (1969) and builds on the bottleneck work of Arnott et al. (1999) who analyzed stochastic capacity and demand on congestible roadways. Fosgerau develops explicit expressions for the expected marginal and total costs associated with random capacity and demand. He concludes that stochastic capacity and demand increases congestion costs up to 50% over deterministic capacity and demand (Fosgerau 2008).

Sheffi et al. (1981) describe the Network Emergency Evacuation Model (NETVAC1), a macro-traffic simulation model that estimates clearing time during the evacuation of the area around a nuclear power plant. The NETVAC1 simulates a

transportation network over several time intervals and uses the mathematical relationships between traffic flow-rate (vehicles/hour), speed (miles/hour (mph)), and density (vehicles/mile) to evaluate the evacuation process. NETVAC1 calculates roadway capacities according to the Highway Research Board Highway Capacity Manual guidelines (Highway Research Board 1965) and updates capacities at the beginning of each simulation interval (Sheffi et al. 1981).

B.   ASSESSING CLEARING TIMES

During hurricanes, state and local emergency managers must ensure complete evacuation of vulnerable regions before the onset of pre-landfall hazards such as gale force winds (Galveston District, U.S. Army Corps of Engineers 2010). Vulnerable regions are those areas that are susceptible to storm surge and flooding. States and counties conduct Hurricane Evacuation Studies (HESs) to identify vulnerable regions for each hurricane category, to assign each region an evacuation priority, and to estimate evacuation clearing times. Accurately assessing the clearing time is essential for safe evacuation of residents.

Emergency managers either mandate or encourage regions to evacuate based on the category of the impending storm. The Saffir-Simpson Hurricane Wind Scale (SSHWS), originally developed by wind engineer Herb Saffir and meteorologist Bob Simpson, lists five categories of storms based on wind intensity. The SSHWS is used to assess property damage and the likelihood of injury and death to persons and livestock for each category of storm (Saffir-Simpson Team 2012). The time required to clear residents from vulnerable regions is a function of the number of evacuating, the discretionary decisions of individual residents about when to leave and where to go, and the road network's capacity.

The decisions of individual residents about when and where to evacuate has been studied and modeled by many scholars, but predictable behavior has not been identified. Jeffrey Czajkowski developed a multi-period model in which households compare the costs of evacuating versus the expected costs of not evacuating in each National Hurricane Center forecast advisory period (Czajkowski 2011). Jason Crews also

considered a multi-period model and used dynamic programming to develop a generic multi-period disaster model in which households decide whether to "stay" or "evacuate" in each period (Crews 2012). Dombroski et al. (2006) studied public compliance with evacuation orders. The study explored social science factors that could potentially affect the behavior and decisions of residents when given the order to evacuate. The general consensus of these studies is that more research needs to be conducted to better understand the impact of resident evacuation decisions on clearing times.

The third component impacting clearing time is the road network capacity, which is defined as the maximum sustainable hourly flow rate at which vehicles can be expected to traverse a road segment in good weather and visibility, with no incidents or accidents, no work zone activity, and no pavement deterioration serious enough to affect traffic (Transportation Research Board 2010). Roadways operating below capacity are said to be under-saturated, while roadways operating above capacity are over-saturated. As saturation levels increase, the speed at which vehicles on the road can travel drastically decreases. The highly unpredictable routing decisions of individual residents can create chaotic traffic patterns which increase saturation levels and, consequently, increase clearing times (Fosgerau 2008).

C.   CLEARING TIME STUDIES

The U.S. Army Corps of Engineers (USACE) conducts traffic flow analyses for counties and states to assess the ability of transportation systems to evacuate residents. In 2010, USACE's Mobile County District updated its estimated hurricane evacuation clearance times for coastal Alabama (Mobile County and Baldwin County) using the 2010 Census Survey data. Table 1 shows estimated clearing times for five evacuation scenarios: one each for Mobile County and Baldwin County evacuating alone; one for mass evacuation of Mobile County, Baldwin County and Northwest Florida; and two scenarios for mass evacuation of Mobile County, Baldwin County, Northwest Florida, Mississippi and Louisiana evacuating with and without I-65 contra-flow (Mobile District, U.S. Army Corps of Engineers 2010).

USACE's evacuation scenarios consider tourist occupancy levels, county evacuation zones for various storm categories and the rate at which residents begin to evacuate. The road network only includes the primary evacuation route established by counties. USACE researchers estimate and model some non-evacuation background traffic but assume local roads can handle most of it. They divide county evacuation zones into traffic evacuation zones (TEZs) and estimate the percentage of residents going to various destinations. They assign a specific set of routes to each TEZ based on the destination of its residents. Clearing times ranged from 10 to 47 hours. The study determined that the bottleneck for evacuating both Mobile County and Baldwin County is along Interstate Highway 65 at Highway 113 in the neighboring Escambia County, Alabama. Table 1 identifies other critical road segments during each scenario.

Clearance Times Summary

	Critical Roadway Segment	Cat 1 Range	Cat 2 Range	Cat 3 Range	Cat 4 Range	Cat 5 Range
Baldwin County	Ala 59 thru Loxley *Includes Mobile thru-traffic* *No Interstate impacts*	10 to 22 hours	15 to 29 hours	15 to 29 hours	22 to 36 hours	22 to 36 hours
Mobile County	I-10 eastbound to Baldwin Co. *Includes Baldwin thru-traffic* *No Interstate impacts*	15 to 20 hours	15 to 20 hours	17 to 23 hours	20 to 25 hours	20 to 25 hours
Additional States	I-65 eastbound with FL w I-10 eastbound (worst case) *Includes LA, MS (eastbound) and FL (westbound)*	15 to 25 hours	21 to 32 hours	25 to 36 hours	34 to 45 hours	36 to 47 hours
	I-65 eastbound with FL (w/o I-10 eastbound) *Includes only FL (westbound), no LA or MS (eastbound)*	15 to 25 hours	21 to 31 hours	24 to 35 hours	33 to 44 hours	34 to 45 hours
Contraflow	I-65 eastbound with FL w I-10 eastbound *Includes LA, MS (eastbound) and FL (westbound)*	15 to 22 hours	15 to 29 hours	17 to 29 hours	22 to 36 hours	23 to 36 hours
Note: *Contraflow benefits on I-65 will not generate clearance times lower than the highest time at the county critical roadway segment for Baldwin or Mobile County.*						

Table 1. U.S. Army Corps of Engineers 2010 clearing time estimates for coastal Alabama. From Mobile District, U.S. Army Corps of Engineers, 2010.

D. ROADWAY AND CAPACITY CONCEPTS

The Transportation Research Board Highway Capacity Manual (HCM) assigns free-flow speed, the speed at which vehicles are unimpeded by other vehicles on the road, and capacity to various types of facilities (roadways) (Transportation Research Board 2010). It also divides them into two general facility types: uninterrupted and interrupted.

The frequency of signalized intersections characterizes a facility's type. Uninterrupted facilities are freeways, multilane highways, and two-way highways. Freeways do not have signalized intersections, and multilane highways and two-way highways have at least two miles between signals. Interrupted facilities consist of urban streets, where signalized intersections are less than two miles apart (Transportation Research Board 2010).

This thesis focuses on uninterrupted facilities. However, approximately 6% of the road segments in the counties studied are interrupted facilities. Modeling interrupted segments involves methodologies for incorporating various signalized delays, mid-block free-flow speeds, lane width adjustments, and other adjustment factors that are beyond the scope of this thesis. For simplicity, we model these segments as uninterrupted facilities.

E.   TRAFFIC FLOW CONCEPTS

Traffic flow is a complex phenomenon encompassing the interactions of vehicles, bicycles, and pedestrians sharing transportation infrastructure. The key to understanding traffic flow and congestion is to understand the relationship between traffic flow rate, speed, and density (Hall 1992). Flow rate (q) measures the number of vehicles passing a reference point over a period of time. Speed (v) measures the distance traveled over a period of time. Density (D) measures the number of vehicles occupying a length of roadway in a particular instant (Transportation Research Board 2010).

Transportation analysts use a variety of traffic flow equations to represent the relationship between the flow rate, speed and density. Wardrop (1952) developed the fundamental flow-speed-density equation:

$$D = \frac{q}{v} \tag{2.1}$$

where
D = density [vehicles/mile/lane]
q = flow rate [vehicles/hour/lane]
v = mean speed of traffic [mph].

The HCM utilizes this widely-accepted equation as the basis for its speed-flow models. Speed-flow models predict speed as a function of flow rate. They are centered on the concept of *free-flow* speed (Transportation Research Board 2010). The underlying assumption of Wardrop's equation is that vehicles move together harmoniously at constant speed. While this is approximately true for under-saturated conditions, over-saturated conditions violate the equation's implied assumption that vehicle spacing remains constant in over-saturated conditions (Hall 1992). Vehicle spacing in over-saturated, slow-and-go congested traffic is not constant. Therefore, HCM methodologies are inadequate to model over-saturated conditions.

F.   AKÇELIK'S TIME-DEPENDENT SPEED-FLOW FUNCTION

Rahmi Akçelik developed the *Time-Dependent Speed-Flow Function* (TDSF), which is both a steady-state queuing delay function for under-saturated conditions and a deterministic delay function for over-saturated conditions (Akçelik 2003). The TDSF estimates travel speed at a given saturation level (called the *degree of saturation, x*). The main parameters describing the TDSF are:

v = speed at a given degree of saturation x [mph]

v_f = free-flow speed [mph]

v_n = speed at capacity [mph]

T_f = duration of the analysis period [hours]

Q = nominal capacity [vehicles/hour]

x_o = degree of saturation below which the traffic delay is zero [dimensionless]

k_d = delay parameter [vehicles/mile^2]

N_i = initial queued demand [vehicles]

q_a = flow-rate [vehicles/hour]

x = degree of saturation [dimensionless]

$$x = (q_a / Q)$$

x' = degree of saturation adjusted to account for N_i effects [dimensionless]

$$x' = x + [N_i / (QT_f)]$$

z = a parameter defined for convenience [dimensionless]

$$z = x - 1 + 2N_i / (QT_f)$$

(Akçelik 2003).

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The TDSF is:

$$v = v_f / \{1 + 0.25\, v_f T_f [z + (z^2 + 8k_d(x - x_o)/(QT_f) + 16k_d N_i /(QT_f)^2)^{.5}]\}$$

$$for\ x' > x_o \qquad (2.2)$$

$$= v_f \qquad\qquad for\ x' < x_o \qquad (2.3)$$

(Akçelik 2003).

When there is no initial queued demand ($N_i = 0$), Equation (2.2) simplifies to:

$$v = v_f / \{1 + 0.25\, v_f T_f [z + (z^2 + 8k_d(x - x_o)/(QT_f))^{.5}]\} \qquad for\ x' > x_o \qquad (2.4)$$

(Akçelik 2003).

Akçelik calibrates this model by using empirical data to assign the appropriate values of v_n / v_f and x_o. He proposes using the following values:

"(i) use the same value of speed ratio for all four classes of basic freeway segments and for all four classes of multilane highways ($v_n / v_f = .85$) for freeways and 0.82 for multilane highways have been selected); and

(ii) use the same value of degree of saturation to determine the flow limit for free-flow speed (or zero traffic delay) for all four classes of basic freeway segments and for all four classes of multilane highways ($x_o = 0.70$ for freeways and 0.65 for multilane highways have been selected)."

Akçelik also suggests using $x_o = 0.50$ for urban streets. Singh (1995) proposes using the values in Table 2 for the delay parameter, k_d:

Roadway Type	Free-flow Speed (mph)	k_d
Freeway	75	0.1
Arterial (uninterrupted)	62	0.2
Arterial (interrupted)	50	0.4
Secondary (interrupted)	37	0.8
Secondary (high friction)	25	1.6

Table 2.   Representative Parameters for TDSF. After Singh, 1995.

III. MASS EVACUATION NETWORK MODEL

This chapter presents the development of the road network studied in this thesis. We model evacuating residents of the 216 census tracts (neighborhoods) of Mobile County, Baldwin County, and Escambia County as outlined in the 2010 Census Survey. The network modeled includes interstate highways, major county roads, and minor county roads. We assume that local roads can handle non-evacuating background traffic.

A. BUILDING THE NETWORK

We start with a collection of road segments extracted from the 2012 U.S. Road Data Base for Network Modeling (Brown and Halwachs 2012). The data for each road segment includes the segment's length in miles and its speed limit in miles per hour (mph). We use nominal capacities as suggested by HCM (2010) and Singh (1995) (detailed in section B of this chapter). Because transportation networks change over time, we use Google Earth, a free online geographical information software (Google, Inc. 2012), to visually verify the existence and number of lanes for each road segment. We keep all road segments verified to exist and discard all others. We manually add road segments where necessary to accurately represent the current road network.

We model the road network using a set of nodes and a set of arcs. *Source nodes* have supplies that can be routed through the network to satisfy demand at *sink nodes*. Nodes that have neither supply nor demand are called *transshipment* nodes. We identify a source node for each census tract (see Figure 1). All residents within a census tract originate from the assigned source node. Using each county's primary evacuation route, we designate exit points outside the vulnerable area as sink nodes. We assign to each segment of the primary evacuation route the number of lanes visually verified via Google Earth. We assign one lane to each segment that is not part of the primary evacuation route.
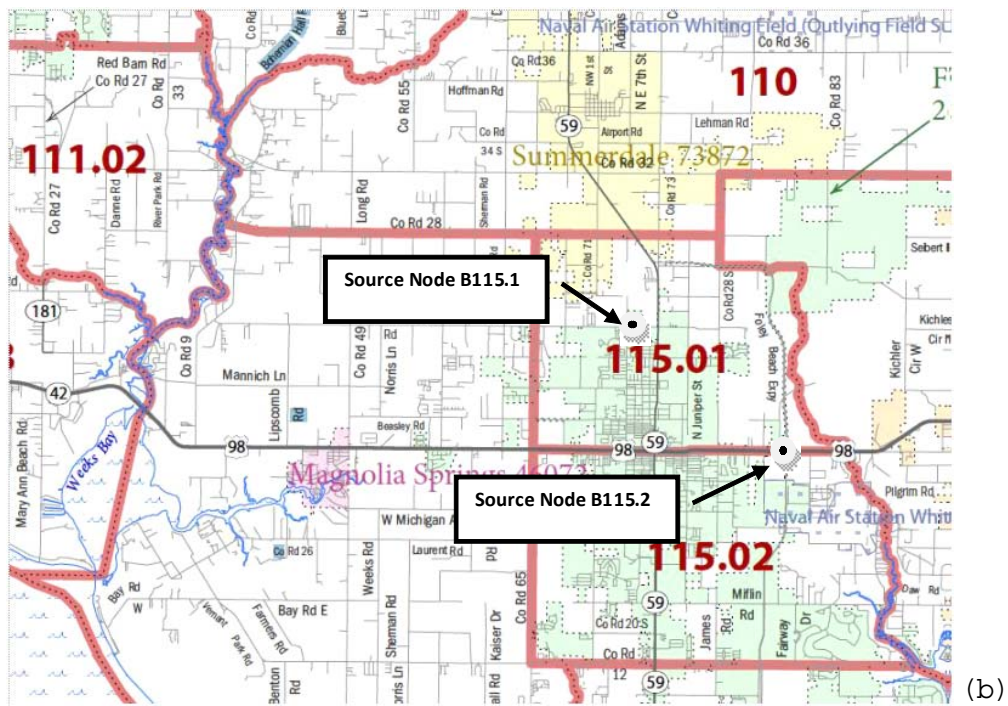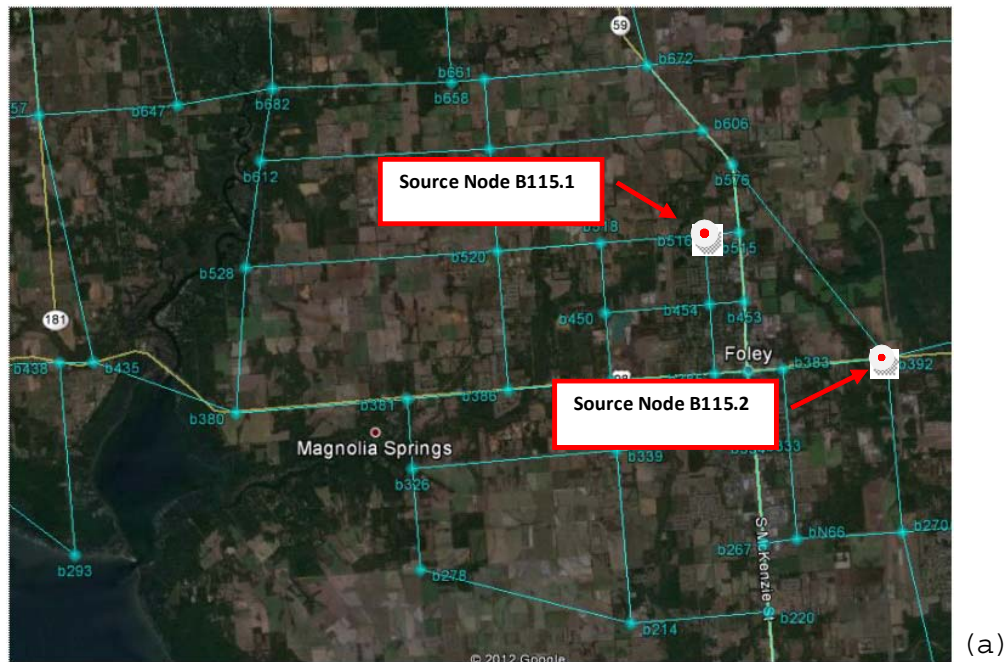
Figure 1.   Partial Baldwin County Google Earth spatial representation (a) and Census Tract map (b).

B. ROAD SEGMENT PARAMETERS

Each road segment has associated parameters that describe its capacity and speed. For each road segment, we determine the values of these parameters in under-saturated (free-flow) conditions. The HCM recommends free-flow speeds and capacities for freeway facilities as shown in Table 3.

Free-Flow Speed (mph)	Capacity per lane (vehicles/hour)
70	2400
65	2350
60	2300
50	2100

Table 3.   HCM freeway facility speeds and capacities.
After Transportation Research Board, 2010.

Singh (1995) also recommends free-flow speed and capacities for various facility types as shown in Table 4.

Type	Free-Flow Speed (mph)	Capacity (vehicles/hour)
Freeway	75	2000
Arterial (uninterrupted)	62	1800
Arterial (interrupted)	50	1200
Secondary (interrupted)	37	900
Secondary (high-friction)	25	600

Table 4.   Free-flow speeds and capacities for various
facility types. After Singh, 1995.

Based on these recommendations, we divide road segments into four categories (I, II, III, and IV) based on their nominal speed and assign to each class a nominal capacity as shown in Table 5.

Road Segment Category	Nominal Speed (mph)	Nominal Capacity per lane (vehicles/hour)
I	60 +	2300
II	50 - 59	1700
III	40 - 49	900
IV	30 - 39	600

Table 5.   Road segment classes used in this study.

We model three congestion levels: no congestion, moderate congestion, and high congestion. When a road segment is operating below its saturation level, no congestion occurs and there is no traffic delay. Moderate congestion occurs when a segment operates at 100% saturation. High congestion occurs in over-saturated conditions; based on Akçelik's TDSF, we use 106% of each segment's free-flow capacity to define high-congestion conditions. Table 6 shows that as congestion levels increase, arc capacity increases and the speed at which vehicles travel decreases.

		CONGESTION LEVELS					
		NONE		MODERATE		HIGH	
Type	Nominal Speed (mph)	Capacity (vehicles/hour)	Travel Speed (mph)	Capacity (vehicles/hour)	Travel Speed (mph)	Capacity (vehicles/hour)	Travel Speed (mph)
I (a)	65	1610	65	2300	28	2438	18
I (b)	60	1610	60	2300	27	2438	17
II (a)	55	1105	55	1700	19	1802	14
II (b)	50	1105	50	1700	18	1802	13
III (a)	45	450	45	900	10	954	8
III (b)	40	450	40	900	9	954	8
IV	30	300	30	600	6	636	5

Table 6.   Sample of segment capacity and travel speed for the three congestion levels.

The moderate congestion level decreases travel speed by more than half of the nominal speed. Figure 2 depicts the speed-flow curve using the Akçelik TDSF. It shows that travel speed decreases rapidly as saturation levels increase.

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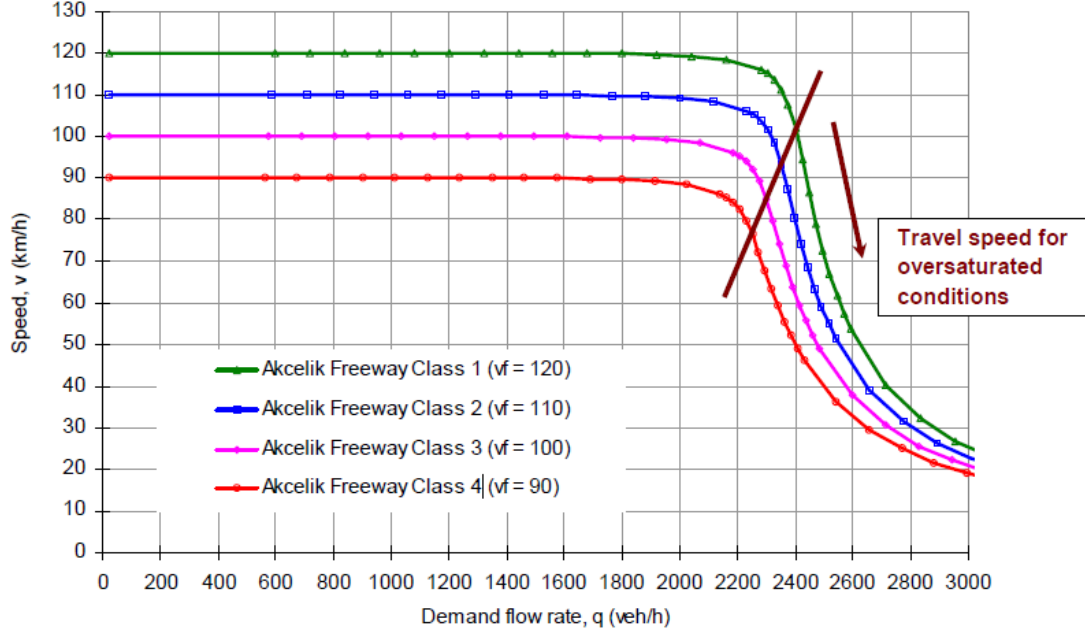
Figure 2.   TDSF speed versus flow-rate for basic freeway segments. From Akçelik, 2003.

We calculate the time (t) required to traverse a segment as its length (l) divided by the travel speed at the given saturation level (v) :

$$t = l/v \qquad (3.1)$$

C.   NETWORK ASSUMPTIONS

For simplicity, we assume roads are empty of traffic when evacuation starts. However, we can model initial traffic by converting the appropriate transshipment nodes to source nodes. Additionally, we do not consider highway on-ramp capacity restrictions. We can model on-ramp capacity restrictions by using additional arcs with lower capacity at the appropriate nodes in the network. We assume that residents evacuate immediately, and we model all vehicles as standard passenger vehicles.

D.   NEIGHBORHOOD SUPPLIES

We calculate the number of vehicles evacuating from each census tract using the 2010 Census Survey vehicle availability statistics. The Census Survey divides households into four categories:

- Households with 1 available vehicle,
- Households with 2 available vehicles,
- Households with 3 available vehicles, and
- Households with 4 or more available vehicles.

For simplification, we assume that all households with 4 or more vehicles have only four vehicles available.

For each household i, the Census Survey provides data on the number of available vehicles a_i and the number of potential drivers o_i. Using this data, we calculate d_i, the number of drivable vehicles in household i, as

$$d_i = \min(a_i, o_i) \tag{3.2}$$

Let H_d be the number of households in a given census tract with exactly d drivable vehicles, where $d = 1, 2, 3, 4$. We assume that each household with available vehicles will use at least one vehicle to evacuate; thus, the minimum possible supply S_{min} originating in the tract is calculated as

$$S_{min} = \sum_d H_d \tag{3.3}$$

The maximum supply introduced in a tract S_{max} is simply the total number of drivable vehicles in the tract:

$$S_{max} = \sum_d d H_d \tag{3.4}$$

Households with multiple occupants may choose to evacuate using one vehicle to ensure that the family evacuates together, or they may use more than one to afford themselves additional flexibility and to remove additional belongings from the vulnerable region. For

simplicity, we calculate each neighborhood's supply V as the average of the neighborhood's minimum and maximum possible supply:

$$V = (S_{min} + S_{max})/2 \qquad (3.5)$$

Figure 3 provides an example of network demand calculation for a census tract with 1420 households with vehicles.

# of Drivable Cars (d)	# Households with exactly d drivable cars (H_d)	
1	458	$S_{min} = \sum_{d} H_d = 1420$
2	688	$S_{max} = \sum_{d} dH_d = 2730$
3	200	$V = (S_{min} + S_{max})/2$
4	74	$= (1420 + 2730)/2$
		$= 2075$

Figure 3.   Example supply calculation for a census tract.

E.   DISCUSSION

The evacuation model is a large, multi-commodity road network. The road network consists of 2710 segments and 825 intersections (i.e., nodes). Commodities are called resident types and represent the 216 census tracts of Mobile County, Baldwin County, and Escambia County. In total, the counties evacuate 433,334 residents: 197,483 for Mobile County, 95,304 for Baldwin County, and 140,547 for Escambia County.

In the next chapter, we develop an evacuation modeling tool that predicts clearing times and minimize the total travel time of evacuating residents.

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IV. MINIMUM COST FLOW WITH CONGESTION SCHEDULING (MCF-CA)

This chapter details the standard Minimum Cost Flow (MCF) model and presents the Minimum Cost Flow with Congestion Scheduling (MCF-CA) formulation, which models congestion during mass evacuations.

A. MINIMUM COST FLOW

The MCF-CA model builds on the standard MCF model and its notation. Thus, we briefly review the MCF formulation. The goal of MCF is to minimize the total cost to move supplies from source nodes to sink nodes (Ahuja et al. 1993, 4–6)

1. Notation

Following the conventions in Ahuja et al. (1993) let $G = (N, A)$ denote a graph, where N is the set of nodes, indexed by n (alias i and j), and A is the set of directed arcs (i,j). Each node n is a junction point that connects two or more arcs. An arc is a segment that provides a path for flow from one node to another. Directed arcs allow flow in only one direction. When flow is allowed in two directions, we use two directed arcs. For example, if a road network has traffic flow in eastward $(i \rightarrow j)$ and westward $(i \leftarrow j)$ directions, then we include arc (i,j) and arc (j,i) are in the set of directed arcs.

Let u_{ij} denote the capacity, or maximum allowable flow, on arc (i,j), where $u_{ij} \geq 0$. Let c_{ij} denote per-unit cost of flow along arc (i,j). Let Y_{ij} denote the flow along arc (i,j). Let s_i denote the exogenous supply at node i (see Figure 2).
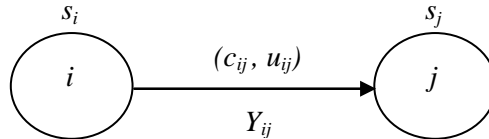

Figure 4. Dumbbell graph representation illustrating flow from node i to node j. After Yuhas, 2012.

2. Formulation

The goal of MCF is to minimize cost:

MCF:

$$Z = \min_{Y} \sum_{(i,j) \in A} c_{ij} Y_{ij} \qquad (4.1)$$

Subject to

$$\sum_{j \in N} Y_{nj} - \sum_{i \in N} Y_{in} = s_n \qquad \forall n \in N \qquad (4.2)$$

$$0 \le Y_{ij} \le u_{ij} \qquad \forall (i,j) \in A \qquad (4.3)$$

Constraint (4.2) is a flow balance constraint. For each node n, the total out-flows minus in-flows must equal the exogenous supply at node n. Constraint (4.3) bounds the flow along each arc (i,j) using the arc's capacity.

B. MINIMUM COST FLOW WITH CONGESTION SCHEDULING (MCF-CA)

In contrast to MCF, MCF-CA is a multi-period model. While MCF's objective is to minimize the cost to move flow through the network, MCF-CA has two objectives. The primary objective is to minimize the number of residents who do not successfully evacuate during the planning horizon, and its secondary objective is to minimize the total cost to move flow through the network. In an evacuation scenario, time is critical. Thus, we use the time required to travel each arc (i,j) as its cost. We model the residents of the 216 census tracts of Mobile County, Baldwin County and Escambia County as individual commodities, and we ensure that for each commodity, the total time spent traveling is appropriate given the length of each time epoch.

In order to model nonlinear congestion effects, MCF-CA selects a congestion level for each arc in each time epoch. This congestion level acts to limit the arc's capacity and uses Akçelik's TDSF Equation (2.4) to determine the average travel speed. MCF-CA uses Equation (3.1) to calculate travel time for each arc based on the congestion level selected. For simplicity, we introduce an artificial node, '*safe*', that is connected to each sink node via an arc with an appropriately large capacity to allow all flow to traverse it (see Figure 5). The cost per unit of flow to traverse an artificial sink arc is zero.
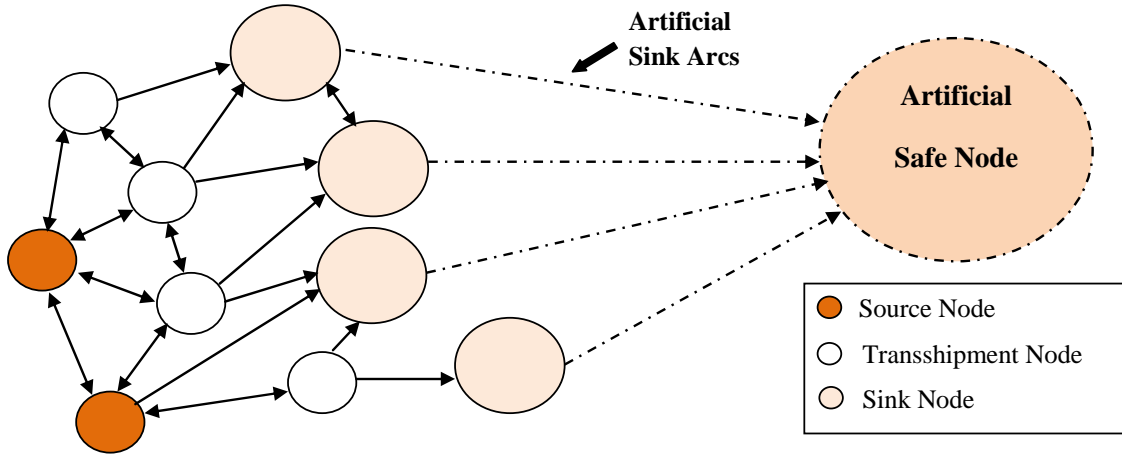
Figure 5.   Network with an artificial "safe" node.

1.   Formulation

MCF-CA:

Index Use [cardinality]:

$n \in N$	nodes, $alias\,(i,\,j)$	[825]
$r \in R$	resident types (commodities)	[216]
$t \in T$	time epochs	[$\sim 6 - 130$]
$l \in L$	congestion level	[3]
$(i,\,j) \in A$	directed arc from node i to node j	[2720]

Data [units]:

s_{nrt}	supply of resident type r at node n during epoch t	$\left[\text{vehicles}\right]$
u_{ijl}	capacity of arc $(i,\,j)$ at congestion level l	$\left[\text{vehicles}\,/\,\text{hr}\right]$
c_{ijl}	time to travel arc $(i,\,j)$ at congestion level l	$\left[\text{minutes}\right]$
p_{n}	penalty for being stranded at node n	[minutes]
e	time length of each epoch	$\left[\text{minutes}\right]$

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Decision Variables [units]:

Y_{ijrlt} flow of resident type r on arc (i, j) at congestion level l [vehicles]

during epoch t

B_{nrt} number resident type r stranded at node n after epoch t [vehicles]

D_{ijlt} binary (1 if congestion level l is chosen, on arc (i, j) [binary]

during epoch t; 0 otherwise)

Formulation

$$Z = \min_{Y,B,D} \sum_{\substack{(i,j)\in A, r\in R, \\ l\in L, t\in T}} c_{ijl} Y_{ijrlt} + e \sum_{\substack{n\in N, r\in R, \\ t\in T}} \left(1+p_n\right) B_{nrt} \tag{4.4}$$

Subject to

$$B_{nrt} = B_{nr(t-1)} + s_{nrt} - \sum_{\substack{(n,j)\in A, \\ l\in L}} Y_{njrlt} + \sum_{\substack{(i,n)\in A, \\ l\in L}} Y_{inrlt} \qquad \forall n \in N, r \in R, t \in T \tag{4.5}$$

$$\sum_{r\in R} Y_{ijrlt} \leq u_{ijl} D_{ijlt} \qquad\qquad\qquad \forall (i,j) \in A, l \in L, t \in T \tag{4.6}$$

$$\sum_{l\in L} D_{ijlt} = 1 \qquad\qquad\qquad\qquad \forall (i,j) \in A, t \in T \tag{4.7}$$

$$\sum_{\substack{(i,j)\in A, \\ l\in L}} c_{ijl} Y_{ijrlt} \leq e \sum_{n\in N} \left(B_{nr(t-1)} + s_{nrt} \right) \qquad \forall r \in R, t \in T \tag{4.8}$$

$$D_{ijlt} \in \{0,1\} \qquad\qquad\qquad\qquad \forall (i,j) \in A, l \in L, t \in T \tag{4.9}$$

$$Y_{ijrlt} \geq 0 \qquad\qquad\qquad\qquad \forall (i,j) \in A, r \in R, l \in L, t \in T \tag{4.10}$$

$$B_{nrt} \geq 0 \qquad\qquad\qquad\qquad \forall n \in N, r \in R, t \in T \tag{4.11}$$

2. Objective Function

MCF-CA's objective function (4.4) contains two terms. The first term mirrors the objective function of MCF and minimizes residents' travel time through network. This term serves two purposes in MCF-CA. First, it ensures that residents take reasonable paths during their evacuation. Second, it helps to ensure that the binary variables D_{ijlt} are set correctly. We elaborate on this function in section IV.B.4.b.

The second term in (4.4) reflects MCF-CA's primary objective, which is to ensure that residents make as much progress as possible toward exiting the vulnerable area during the planning horizon. We assign to each node n a stranding penalty p_n

proportional to the cost (in minutes) of the shortest path from n to *'safe'* in maximum congestion. This penalty encourages residents to move closer to a sink node during epochs when the network does not have enough capacity for complete evacuation. Successfully evacuated residents are stranded at the *'safe'* node, with a penalty cost of *-2* to reward residents for successful evacuation. The stranding penalty term is multiplied by the epoch length, *e*, in order to ensure that the primary objective to evacuate all residents supersedes the secondary objective of minimizing travel time. The epoch length e is a sufficiently large multiplier because residents cannot travel longer than the epoch time length in any given period.

3. Constraints

Constraint (4.5) is similar to the balance of flow Equation (4.2). It is a bookkeeping constraint that records the number of residents stranded at node n at the end of each epoch. Constraint (4.6) is similar to constraint (4.3) in that it bounds the flow on each arc to the arc's capacity. Constraint (4.7) selects exactly one congestion level for each arc. Constraint (4.8) limits the average cumulative travel time of each resident type to at most the epoch length in order to ensure that residents do not travel excessively long. This is a relaxed constraint for limiting each vehicle's travel time. In principle, residents could be modeled as 433,334 individual commodities, and each vehicle's travel time could be limited. However, microscopic evacuation patterns are beyond the scope of this thesis. Constraints (4.9)-(4.11) declare variables types.

4. Discussion

Here we discuss the role of the objective function value and provide an example of how the appropriate congestion level is selected in order to minimize clearing time. We also discuss model implementation and solution times.

a. *Objective Function Value and Clearing Time Estimation*

MCF-CA's objective function value does not explicitly calculate clearing time. Rather, it is designed to reflect the behavior of residents with imperfect knowledge

of future conditions but a desire to move quickly toward safety. It reflects the cumulative travel time of all residents and the penalties incurred for stranding residents in each time period.

Given an optimal solution to MCF-CA, we calculate clearing time during post-optimality analysis. The approximate clearing time (rounded to the next hour) is simply the number of 60-minute epochs required to evacuate all residents. We can derive tighter bounds for the clearing time by analyzing the flows in the last epoch; however, such analysis is beyond the scope of this thesis.

b. Selection of Congestion Level

MCF-CA limits the flow on each arc such that the sum of all flows on the arc does not exceed the arc's capacity, given its congestion level. Note that by itself, constraint (4.6) allows MCF-CA to select a higher level of congestion than is required to accommodate the optimal flows. For example, let congestion levels $l=1$, $l=2$, and $l=3$ denote the states of no congestion, moderate congestion, and high congestion, respectively. Let F_{ijt} denote the total flow on arc (i, j) in epoch t, and suppose that arc (i, j) experiences total flow $F_{ijt} = \sum_{r,l} Y_{ijrlt} < u_{ij2}$ in an optimal solution. MCF-CA can satisfy constraint (4.4) by setting either $D_{ij2t} = 1$ or $D_{ij3t} = 1$. However, if $F_{ijt} > 0$ then we must have D_{ij2t} in an optimal solution, since $D_{ij3t} = 1$ would result in higher (worse) value for the first term in (4.4) and no change in the second term in (4.4). Furthermore, the left hand side of constraint (4.8) is greater when $D_{ij3t} = 1$ than when $D_{ij2t} = 1$. Thus, constraint (4.6) and the first term of the objective function (4.4) work together to ensure that the variables D_{ijlt} accurately reflect the minimum level of congestion required to evacuate all residents in minimum time for all (i, j, t) for which $F_{ijt} > 0$. Since MCF-CA can set D_{ijlt} arbitrarily when $F_{ijt} = 0$, we analyze congestion level selections for only those (i, j, t) combinations for which $F_{ijt} > 0$.

c. *Model Implementation*

We solve MCF-CA with a 1-epoch lookahead using GAMS/CPLEX 12 and run it on computers equipped with an Intel 3.0GHz processor and 96GB of RAM. The largest single-county evacuation, Mobile County, generates over 98,000 constraints, 470,000 variables, 2,000,000 non-zeroes, and over 3,000 discrete variables for each 60-minute time period; its solution time is approximately 12 hours. The mass evacuation generates over 189,000 constraints, 1,900,000 variables, 9,000,000 non-zeroes, and over 8,000 discrete variables for each 60-minute time period; its solution time is approximately 2.5 days.

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V. RESULTS AND ANALYSIS

We now use MCF-CA to analyze clearing times for Mobile County, Baldwin County, and Escambia County during both single-county evacuations and during a three-county mass evacuation.

A. COMPARISON OF COUNTY AND MASS EVACUATIONS

USACE measures the number and destination of evacuees by comparing normal everyday traffic patterns to the traffic patterns during the evacuation, both within the region and immediately outside of the region near exit points (Mobile District, U.S. Army Corps of Engineers 2010). They attribute traffic volume spikes to the movement of residents from the evacuating region. During county-only evacuations, residents compete with normal traffic volume just outside the county at exit points. However, during mass evacuations of multiple counties, the road segments immediately outside of a county are already experiencing increased traffic volume due to the evacuation efforts of the neighboring county. This forces residents to compete for access to road segments with traffic volumes well above the normal pattern.

For each county, we solve MCF-CA to establish a best-case clearing time when residents follow optimal routes and no road impediments occur. Figure 6 displays the clearing times for all counties evacuating in isolation and during a mass evacuation. As the figure indicates, Escambia County's best-case clearing time is 7 hours during a single-county evacuation and 11 hours during a mass-evacuation; Mobile County's best-case clearing time is 14 during a single-county evacuation and 15 hours during a mass evacuation; and Baldwin County's best-case clearing time is 6 during a single-county evacuation and 15 hours during a mass evacuation. As expected, clearing times for the mass evacuation are substantially greater than those of county evacuations. Clearing times increase by 7–133% when counties evacuate together. Baldwin County bears the brunt of mass evacuation because it is geographically sandwiched between Mobile

County and Escambia County. Residents from both Mobile and Escambia Counties flow through Baldwin to evacuate. The influx of residents significantly impede the evacuation flow of Baldwin County residents.
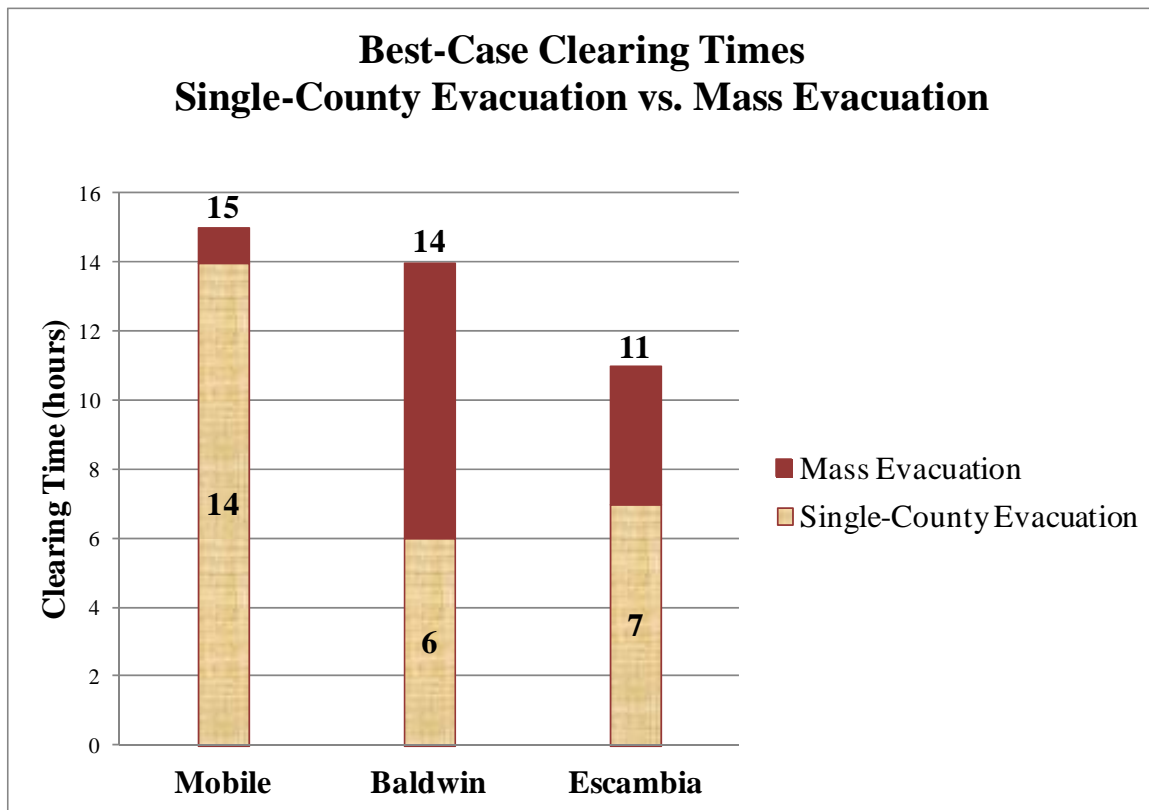

Figure 6.   Best-case single-county and mass evacuation clearing times.

Figure 7 shows the hourly percentage of residents evacuated during county and mass evacuations. By hour 7 during single-county evacuations, both Baldwin County and Escambia County are completely evacuated. However, during mass evacuations, these counties have evacuated only 70% and 80% of their residents, respectively. By hour 7, Mobile County has evacuated only slightly fewer residents during the mass evacuation, 41% versus 51%.
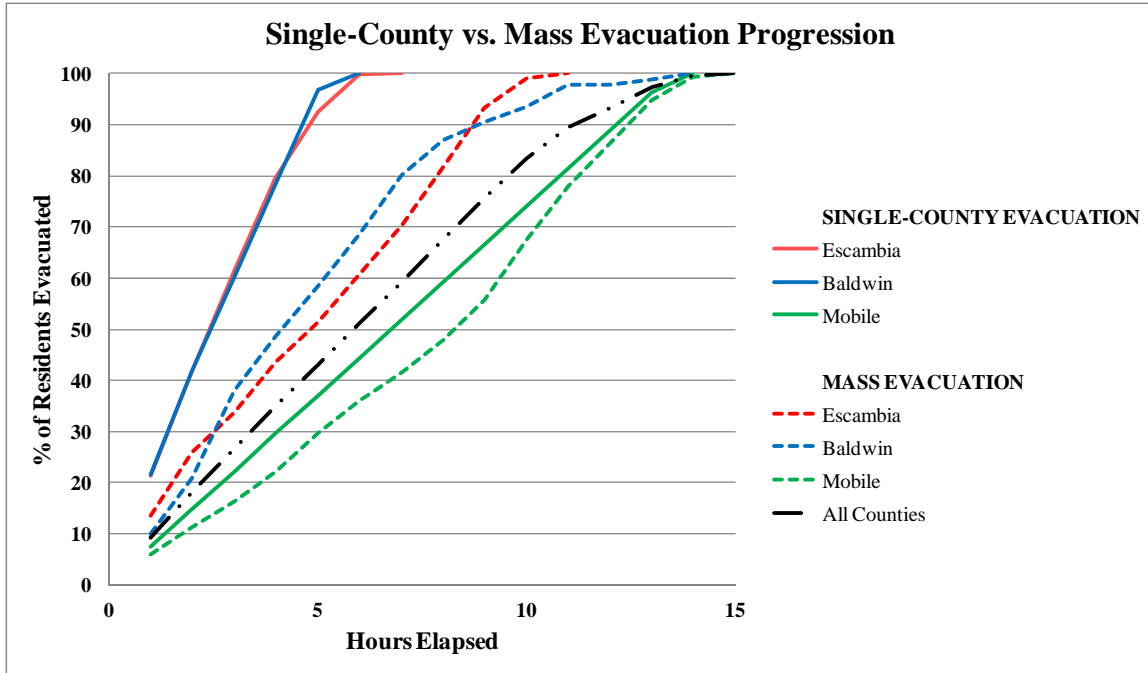
Figure 7.   Single-county clearing times compared to mass evacuation clearing times.

Escambia County's clearing time increases by 57% in part because three of the nine exit points utilized during its single-county evacuation flow into Baldwin County (see Figure 8). Figure 9 reveals that 39.5% of Escambia County residents use the exits at Hwy 98W, Hwy 90W, and I-10W during single-county evacuations. However, these exits are still within the vulnerable region during mass evacuations involving Baldwin County. Consequently, residents either reroute to other exits within the county or reroute to the exits of the adjacent counties. Residents increase their use of exits within the county by as much as 80%. Additionally, approximately 7% use Baldwin County's I-65N exit. Both adjustments result in increased flow through fewer exits, thereby, prolonging the time required to move all residents out of the vulnerable area and increasing clearing times.
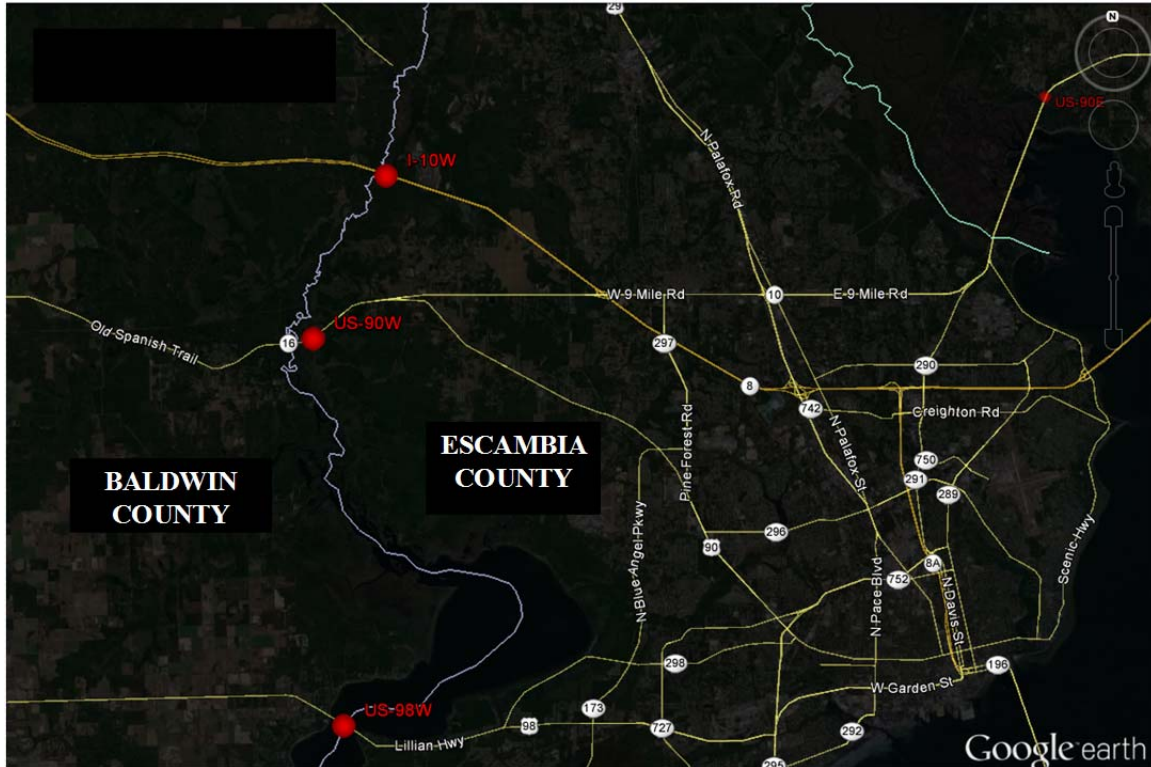
Figure 8.   Escambia County's exits I-10W, U.S.-90W, and U.S.-98W are located on the Baldwin County border and thus do not exit the vulnerable region during a mass evacuation. After Google, Inc., 2013.
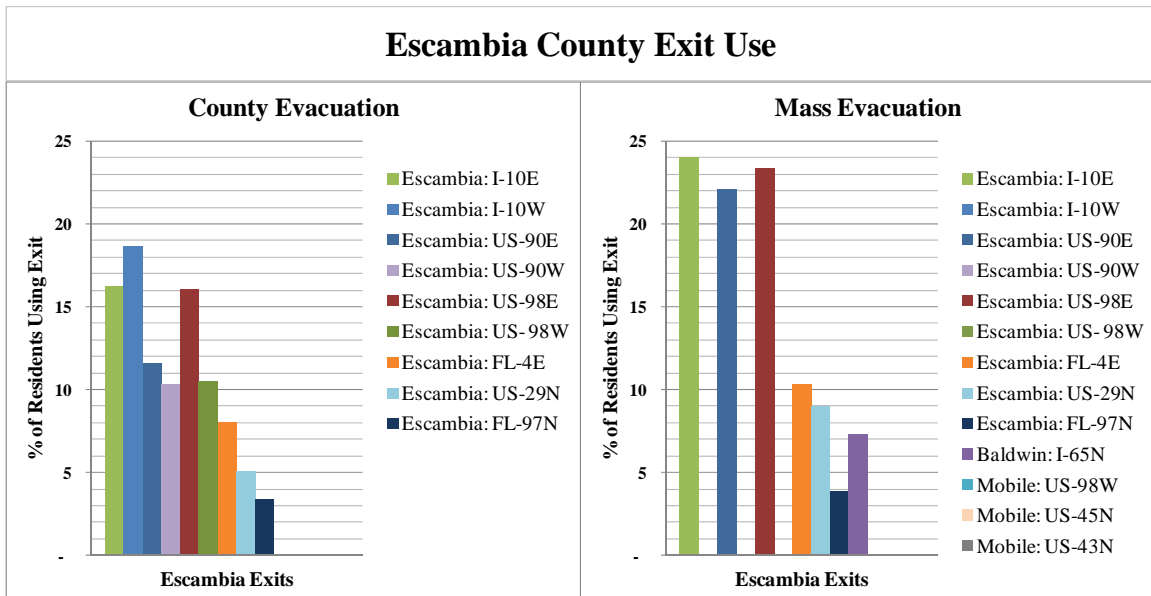

Figure 9.   Escambia County evacuation exit use for all scenarios.

Mobile County's clearing time is minimally impacted during the mass evacuation. Although residents lose the original Mobile County I-65N exit just outside the county, they take advantage of Baldwin County's north-bound contra-flow and move 29% of residents through Baldwin County I-65N exit (see Figure 10). Mobile County residents travel an additional 22 miles to the Baldwin County I-65N exit. However, this shift benefits Mobile County residents by alleviating the need to reroute as many residents to the other exits within the county which would prolong clearing times, as seen in the case of Escambia County. Figure 11 shows the proximity of the two exits. Here, the close proximity of the exits benefits the mass evacuation effort of Mobile County.

Baldwin County's clearing time more than doubles during mass evacuations because it loses one of its two exits (I-10W). As a result, an additional 10% of Baldwin County residents use the remaining I-65N exit (see Figure 12). The remaining 45% who change their exit travel as much as 60 miles through either Mobile County or Escambia County to evacuate.
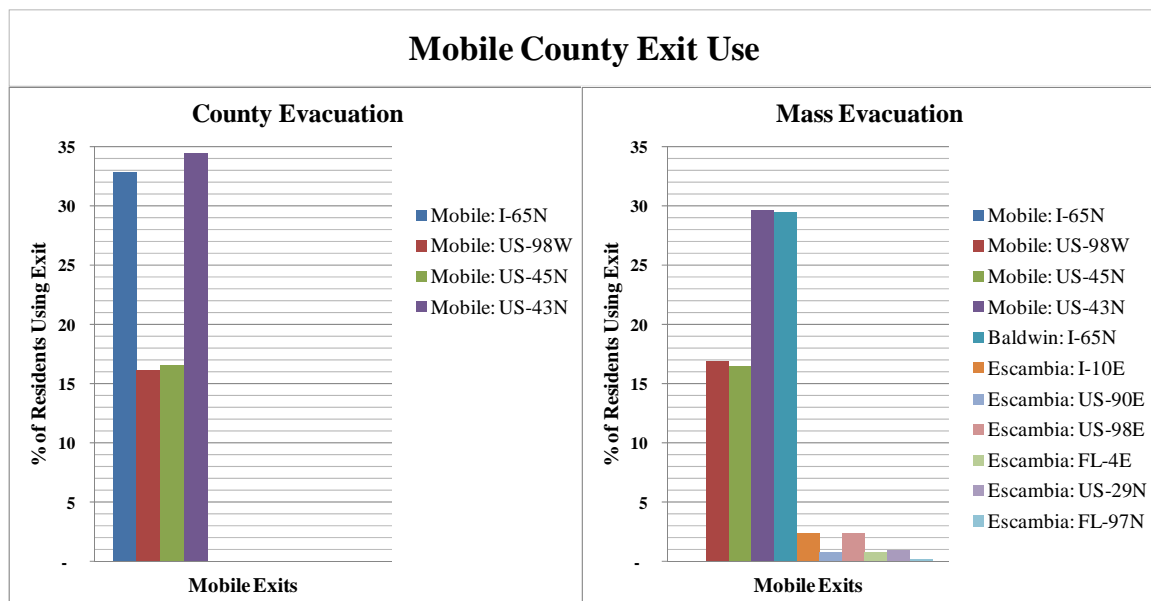

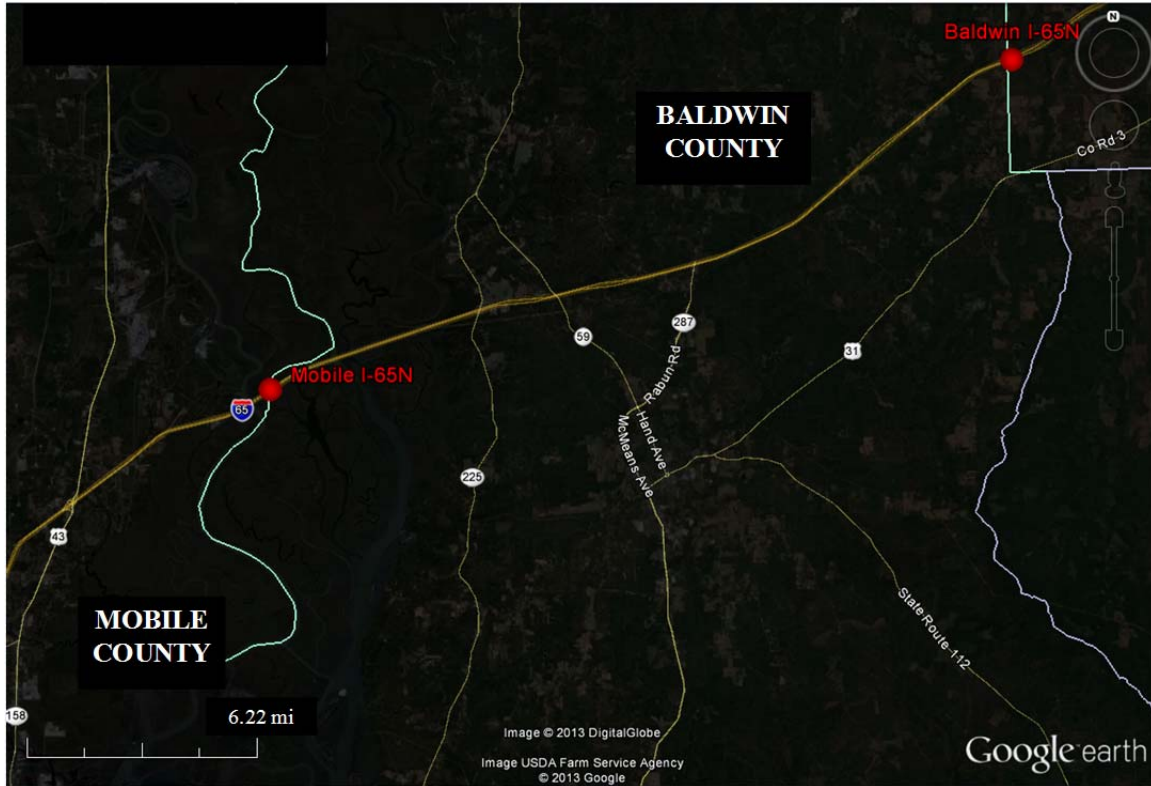Figure 10.   Mobile County exit use during county and mass evacuations.

Figure 11.   Baldwin County I-65N exit location and Mobile County I-65N exit
              location on the border of Baldwin County. After Google Earth, 2013.

These findings demonstrate the significance of exit locations during evacuation. During mass evacuations, some of the exits that residents rely upon for county evacuations are still within the vulnerable region. Consequently, either residents reroute to the remaining exits in the county or travel upwards of 60 miles to evacuate through the neighboring county. In the case of Mobile County, residents may travel two counties over to exit the vulnerable region. In either circumstance, loss of exits during mass evacuations increases clearing times substantially.

We note that this solution is only one of multiple optimal solutions. The solver does not discriminate between the various resident types. Therefore, when more than one type of resident is stranded at a node in the same epoch, the solver arbitrarily chooses which residents utilize which routes. Moreover, the solver could generate a different

optimal solution by choosing a different combination of resident types to move. Emergency managers must keep in mind that multiple optimal solutions may exist for the evacuation problem.
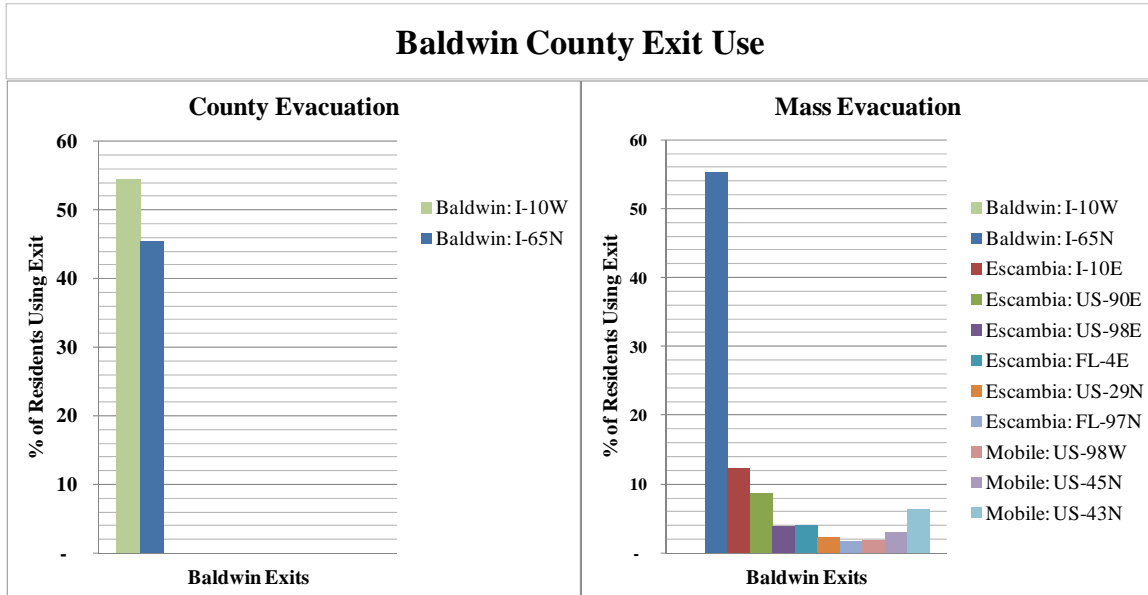

Figure 12.   Baldwin County exit use during county evacuations.

B.   VALIDATION AND COMPARISON WITH EXISTING MODELS

We compare MCF-CA's clearing time results for Mobile County and Baldwin County single-county evacuations to those described in the USACE 2010 study of coastal Alabama (Mobile District, U.S. Army Corps of Engineers 2010). We find that in general, MCF-CA's clearing times tend to be lower than USACE's clearing times.

MCF-CA's best-case clearing time for Mobile County is 14 hours and uses a network supply of 197,483 vehicles evacuating to outside of the county. The comparable USACE Category 5 *Immediate Response* scenario generates a 20-hour clearing time using a network supply of 132,932 vehicles evacuating to outside of the county (Mobile District, U.S. Army Corps of Engineers 2010). The MCF-CA clearing time for Mobile County is 30% shorter than USACE's clearing time.

Similarly, MCF-CA's best-case clearing time for Baldwin County is 6 hours and uses a network supply of 95,304 vehicles evacuating to outside of the county. The

comparable USACE Category 5 *Immediate Response* scenario generates a 26-hour clearing time using a network supply of 63,578 vehicles evacuating to outside of the county (Mobile District, U.S. Army Corps of Engineers 2010). The MCF-CA clearing time for Baldwin County is 77% shorter than USACE's clearing time.

Both MCF-CA estimates are well below the clearing times generated by USACE. However, the MCF-CA's clearing times represent a utopian scenario in which all residents cooperate to minimize the number of stranded residents in each epoch and minimize the total travel time of residents. The USACE model, on the other hand, restricts residents to specific evacuation routes. Because MCF-CA has no restrictions on resident routing decisions, it generates lower clearing times than USACE's restricted model. For a better comparison, in the next section we explore scenarios in which some residents do not evacuate in the most "socially optimal" manner.

C.   IMPACT OF SUB-OPTIMAL ROUTING

The previous section considered the best-case scenarios for Mobile County, Baldwin County, and Escambia County. However, there are several potential reasons why best-case clearing times are not achieved during real-life evacuations, such as resident response time, resident destination choice and resident routing decisions. In this section, we investigate the impact of sub-optimal routing decisions on the part of residents.

1.   Scenarios

Disasters elicit a multitude of evacuation scenarios. According to Cheng et al. (2008), residents have many destination choices and may proceed differently in each evacuation. Most studies, including the USACE Mobile County District study of coastal Alabama, assign evacuees to destinations using specific routes (Cheng, Wilmot and Baker 2008). The USACE Mobile County District study states that residents tend to "follow the leader" during evacuations, unlike normal workday travel when they may venture to choose alternate routes (Mobile District, U.S. Army Corps of Engineers 2010).

In Section A, we model residents making optimal routing decisions and evacuating via any route possible. However, in this section, we model suboptimal routing decisions by adjusting MCF-CA's objective function to incentivize residents to follow their own shortest paths rather than the "socially optimal" routing. Let SP_r denote the set of arcs (i, j) on the shortest path for resident r, and let w denote the incentive for residents to use arcs on their shortest path. Then, the updated MCF-CA objective function is:

$$Z = \min_{Y,B,D} \sum_{\substack{(i,j) \in A, r \in R, \\ l \in L, t \in T}} c_{ijl} Y_{ijrlt} + e \sum_{\substack{n \in N, r \in R, \\ t \in T}} (1 + p_n) B_{nrt} - w \sum_{\substack{(i,j) \in SP_r, \\ l \in L, t \in T}} Y_{ijrlt} \qquad (5.1)$$

Incentivizing residents to use their shortest path effectively decreases the flexibility in route choice for residents, similar to studies that use designated evacuation routes. We examine clearing times for various incentive levels, with incentive levels selected so as to elicit particular routing behavior on the part of the residents. In particular, for each county, we compare four scenarios:

- *Global Cooperation*: Residents collectively optimize their evacuation,
- *Moderate Cooperation*: Approximately 50% of residents use their shortest path,
- *Low Cooperation*: Approximately 75% of residents use their shortest path, and
- *No Cooperation*: All residents use their shortest path.

Note that the *Global Cooperation* scenario is equivalent to that considered in the section A, while the other scenarios consider progressively more myopic routing decisions on the part of the residents.

2. Impact of Sub-optimal Routing on Clearing Times

Figures 13–15 show that clearing times increase dramatically more residents use their shortest path. Escambia County's clearing time ranges from 7 to 20 hours, Baldwin County's clearing time ranges from 6 to 23 hours, and Mobile County's clearing time ranges from 14 to 48 hours. For all counties, we see that in the *No Cooperation* scenario, clearing time is two to four times that of the *Global Cooperation* scenario. *Low*

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Cooperation decreases clearing time by 6–39% from that of *No Cooperation*, while *Moderate Cooperation* decreases clearing times by another 13–21%. Note that evacuation percentages for all suboptimal routing scenarios quickly diverge from those of the *Global Cooperation* scenario as early as the second hour of evacuation. This finding is important because it highlights the important of residents' route choices in establishing clearing times.
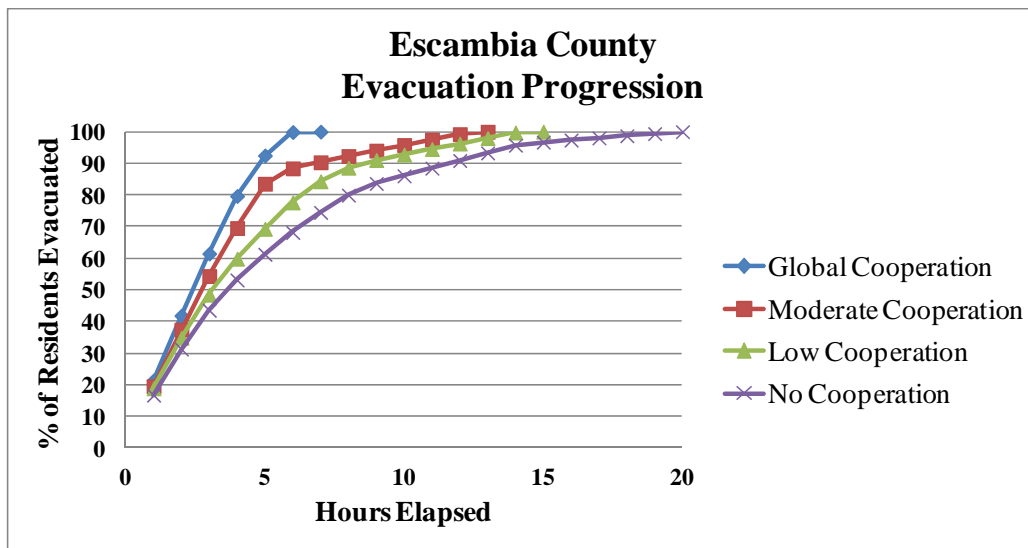

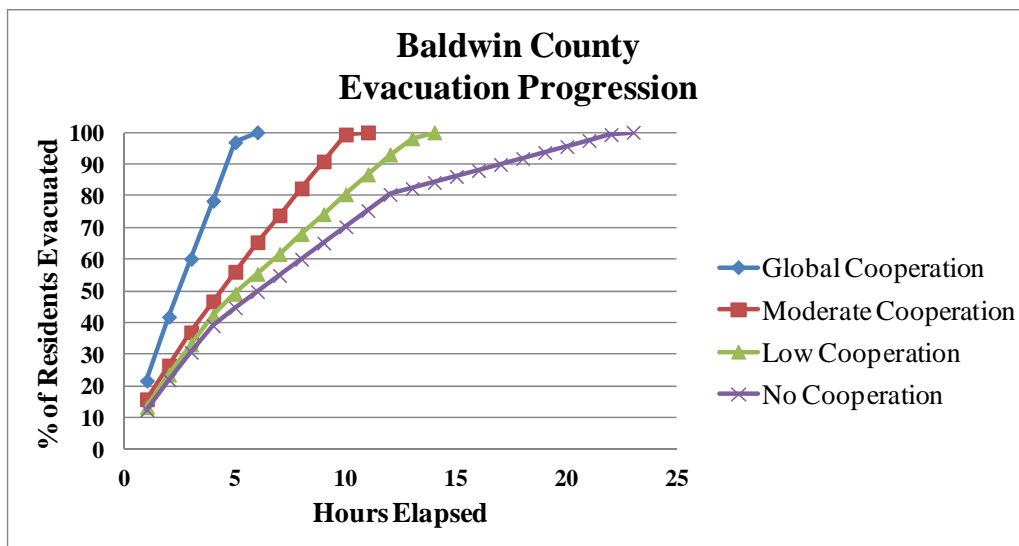Figure 13.   Escambia County hourly evacuation progression for all scenarios.

Figure 14.   Baldwin County hourly evacuation progression for all scenarios.
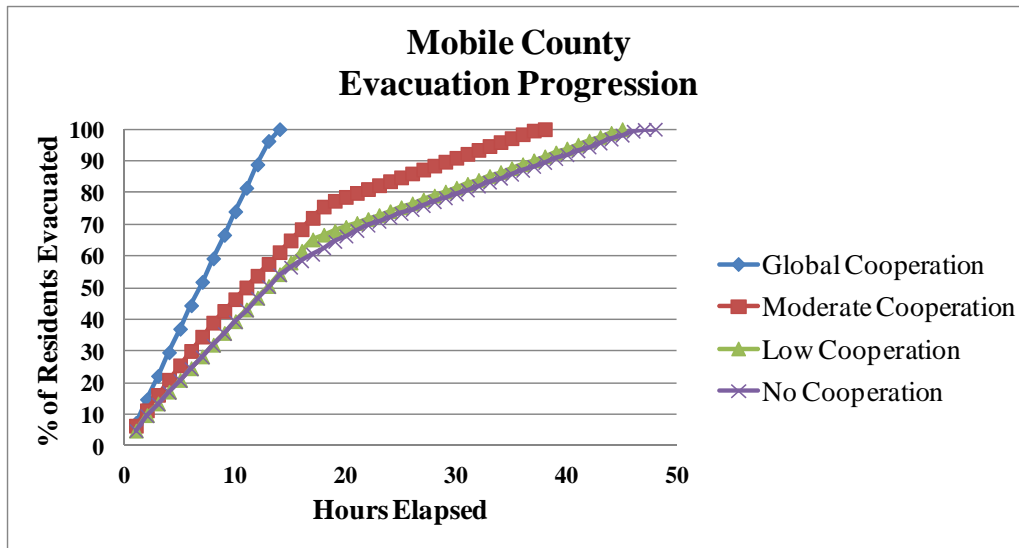
Figure 15.   Mobile County hourly evacuation progression for all scenarios.

Mobile County's *No Cooperation* clearing time grows to more than 200% of its *Global Cooperation* time. Figure 16 reveals that almost 100% of the Mobile County's residents are closest to two of the four designated exit points, I-65N and U.S.-98W. So, as more residents follow their shortest path, the remaining two Mobile County exits, U.S.-45N and U.S.-43N, are under-utilized. We also observe that Mobile County's *Global Cooperation* flow use exits more efficiently to start evacuating more residents more quickly. By the eighth hour of evacuation, *Global Cooperation* evacuates 20% more residents than *Moderate Cooperation*. And by hour 14 when *Global Cooperation* completes evacuation, the other scenarios have evacuated just a little over 50% of residents.

This finding is important because it demonstrates that while having many exit points established is desirable to having a few, residents must sometimes be encouraged to use exits that are distant to ensure timely evacuation of all residents. Thus, intelligent routing decisions by residents are the key to ensuring an efficient evacuation.
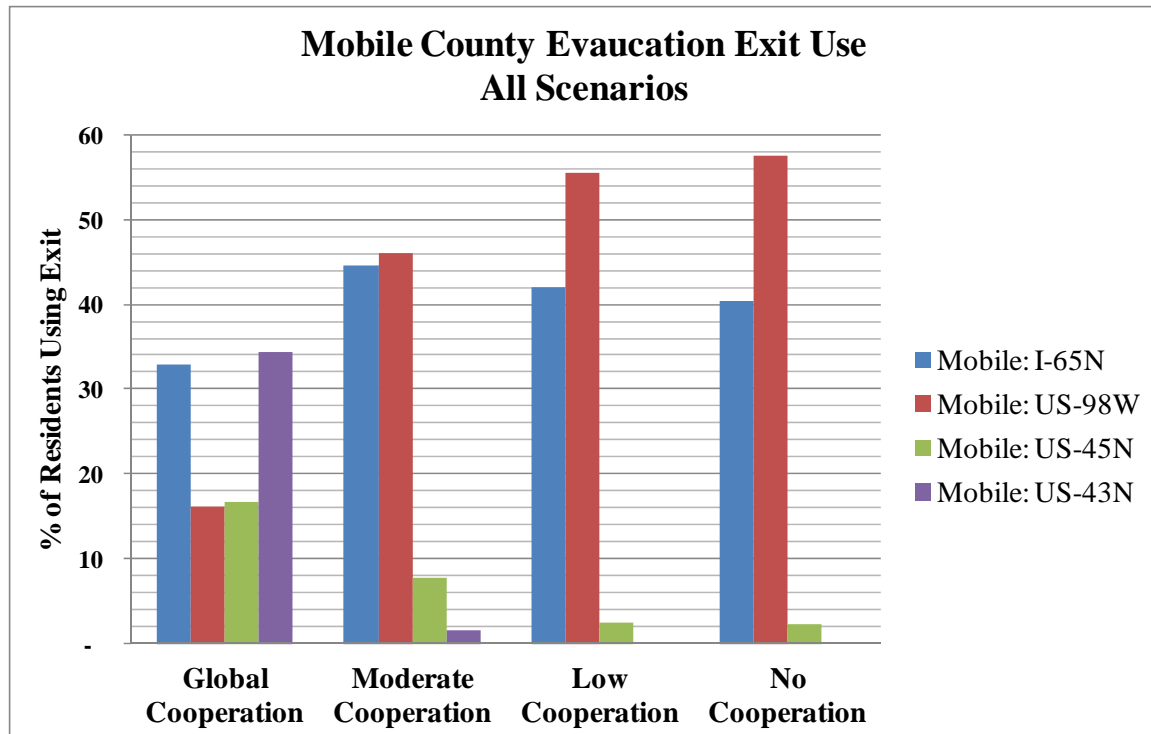
Figure 16.   Mobile County exit use for all scenarios

3.   Suboptimal Routing Validation and Comparison with Existing Models

We again compare MCF-CA's clearing time results for Mobile County and Baldwin County to those described in the USACE 2010 study of coastal Alabama (Mobile District, U.S. Army Corps of Engineers 2010). We use the USACE 1999 Northwest Florida Hurricane Evacuation Study Technical Data Report (U.S. Army Corps of Engineers 1999) to validate Escambia County clearing times. We use the clearing times of the *Global Cooperation* and *No Cooperation* scenarios, shown in Figure 17, as lower and upper bounds for comparison.

County Evacuation Clearing Times
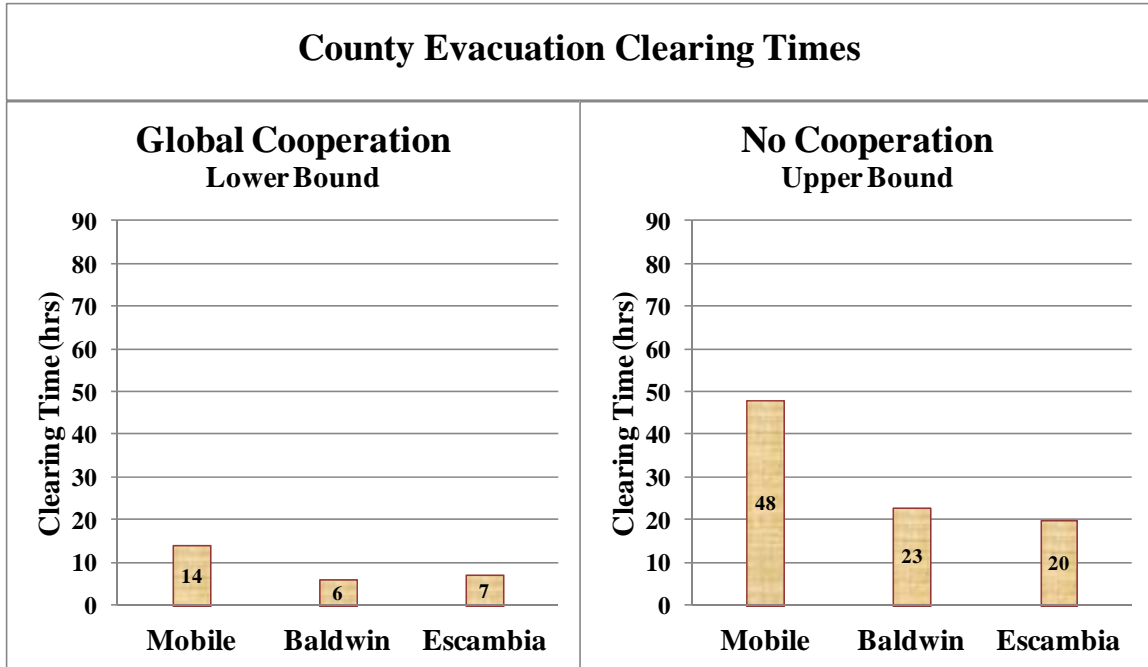
| Global Cooperation | No Cooperation |
| Lower Bound | Upper Bound |

Figure 17.   MCF-CA-generated clearing times for all single-county evacuations.

4.   Mobile County Clearing Time

MCF-CA's clearing time for Mobile County ranges from 14 to 48 hours. As discussed in section B, the comparable USACE's Category 5 *Immediate Response* scenario generates a 20-hour clearing time (Mobile District, U.S. Army Corps of Engineers 2010), which falls within the upper and lower bounds of the times generated by MCF-CA. However, USACE evacuates only 132,932 vehicles to outside the county, while MCF-CA evacuates 197,483.

We see that USACE's Category 3 *Immediate Response* scenario generates a 17-hour clearing time and evacuates 10,193 fewer vehicles to outside the county than the Category 5 scenario (Mobile District, U.S. Army Corps of Engineers 2010). Thus, we assume that the additional clearing time hours are solely attributed to the increased number of residents evacuating outside the county. Namely, an increase of 10,193 vehicles adds 3 hours to Mobile County's clearing time. Although we cannot extrapolate this finding to determine the impact of an additional 64,551 vehicles, we can surmise that a complete evacuation of all residents (almost 200,000 vehicles) is well beyond the 20-

hour clearing time cited by the USACE. Moreover, the clearing times generated by MCF-CA, 14 to 48 hours, are consistent with the USACE's results.

5.   Baldwin County

MCF-CA's clearing time for Baldwin County ranges from 6 to 23 hours. USACE's comparable Category 5 *Immediate Response* scenario generates a 26-hour clearing time (Mobile District, U.S. Army Corps of Engineers 2010), well above the times generated by MCF-CA. Surprisingly, although Mobile County evacuates more than twice the number of vehicles as Baldwin County (197,483 and 98,304, respectively), USACE's estimated clearing times for Baldwin County are significantly greater than those for Mobile County.

Baldwin County's USACE clearing time accounts for normal Mobile County through-traffic flow. We test the impact of higher non-evacuation traffic by decreasing the capacity of the arcs leading to both of Baldwin County's exit by 50%. Clearing time increases slightly to 14–32 hours when we reduce capacity of arcs leading to I-10W and I-65N.

While these results are similar to the 26-hour clearing time given by the USACE, additional corroboration is desirable. Unfortunately, the most recent post-hurricane assessment for a Category 3 or higher storm is the 2009 Post Storm Assessment: Hurricanes Gustav and Ike (Mobile District, U.S. Army Corps of Engineers 2009). The report does not provide usable data to assess evacuation clearing times for Baldwin County. It states that Baldwin County evacuated "zero" and a "small number" of residents for Hurricanes Ike and Gustav, respectively (Mobile District, U.S. Army Corps of Engineers 2009).

6.   Escambia County

The 1999 USACE HES for Northwest Florida shows Escambia County's projected 2005 clearing time for a Category 5 hurricane is 16.5 hours (U.S. Army Corps of Engineers 1999). The clearing time is based on 100% evacuation, rapid response, and low seasonal occupancy. Population growth in addition to road improvements since 1999

may cause the clearing times to be slightly different from those reported in the HES. However, the most current USACE HES clearing time is within the 7–20 hour range generated by MCF-CA.

D.   OCCURRENCE AND BENEFITS OF CONGESTION

In this section we examine when and how congestion occurs during the evacuation process. Using the four scenarios developed in the previous section, we investigate congestion when residents cooperate and when they do not. We then restrict MCF-CA to disallow congestion in all arcs in all time epochs. Restricting MCF-CA to disallow congestion models an ideal controlled departure system that maximizes vehicle travel speed during evacuations. We study the impact of this restriction on clearing times.

1.   Impact of Congestion with Sub-optimal Routing

Figure 18 displays Mobile County residents' evacuation progression and the percentage of roads utilized in each epoch that are road congested. We see that congestion persists throughout the evacuation horizon. We expect to see higher levels of congestion associated with long clearing times and low levels of congestion associated with short clearing times. However, that assumption is incorrect for all county evacuations.

The percentage of utilized roads that are congested for both the *Low Cooperation* and *Moderate Cooperation* scenarios rise above *No Cooperation* at various points in the evacuation process. The first time *Low Cooperation* rises above *No Cooperation* is in hour 12. Up to this point, approximately 47% of residents have evacuated in both scenarios. At hour 12, additional residents start moving on the road network in *Low Cooperation* while no additional residents start moving in the *No Cooperation*. More roads are congested in the *Low Cooperation* scenario simply because more arcs are utilized. We see similar results for both Escambia County and Baldwin County (see the Appendix).
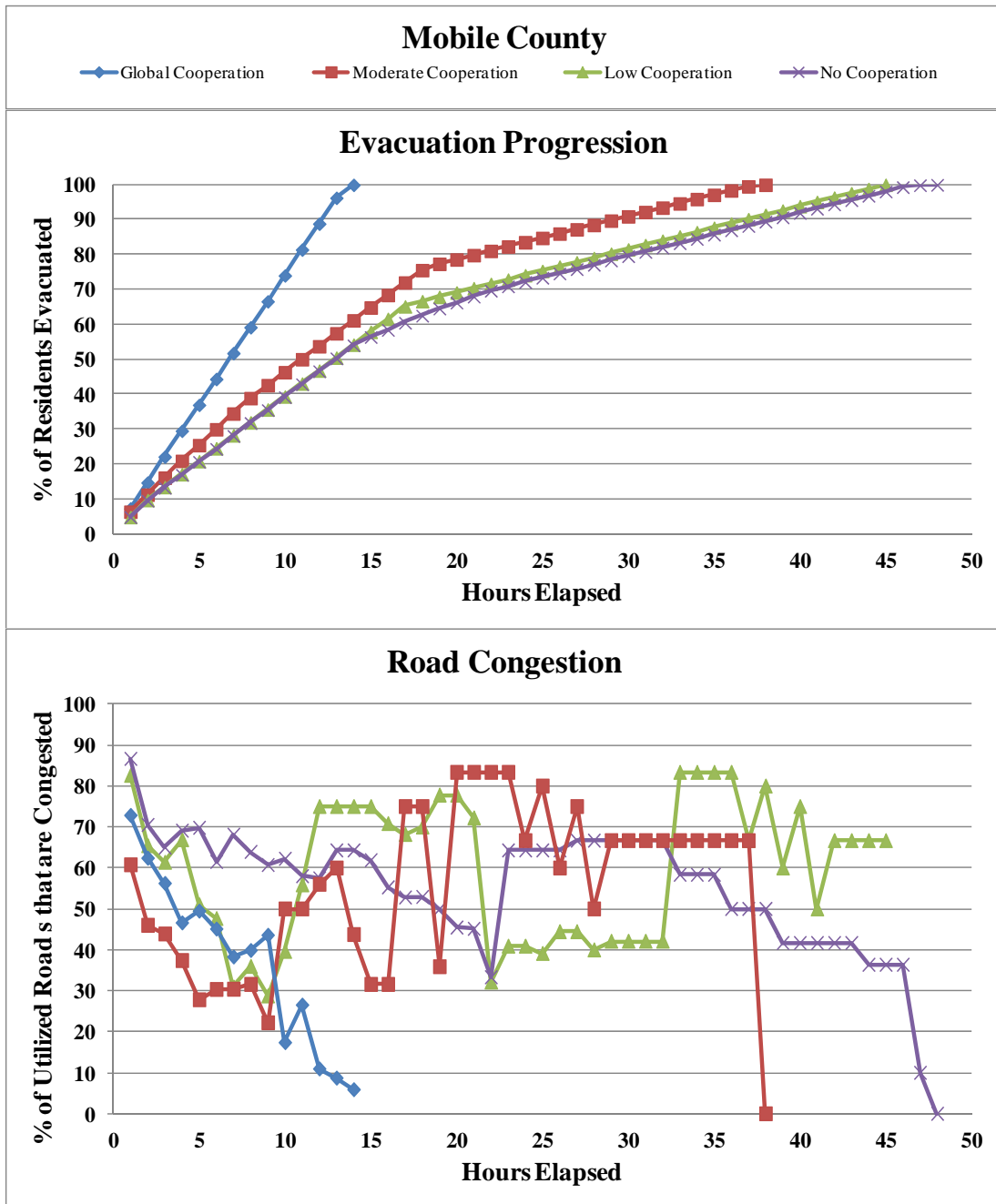
Figure 18. Mobile County evacuation progression and road congestions.

2. Resident Congestion

While it is useful to examine the percentage of road segments that experience congestion, it is perhaps more instructive to consider the percentage of residents that encounter congestion during their evacuation. Figures 19–21 show the percentage of

residents in each county that experience congestion at some point during the evacuation horizon and the total number of arcs that are congested. We see that more than 50% of residents in each county experience congestion.

We observe that the percentage of residents who experience congestion is lowest in scenarios in which more arcs are congested. *Global Cooperation* has the lowest percentage of residents that experience congestion, the shortest clearing time, and the highest number of congested arcs. The flexibility in route choice that *Global Cooperation* affords increases the number of arcs used, thereby increasing the number of congestible arcs. This result implies that increased flexibility in route choice improves clearing time.
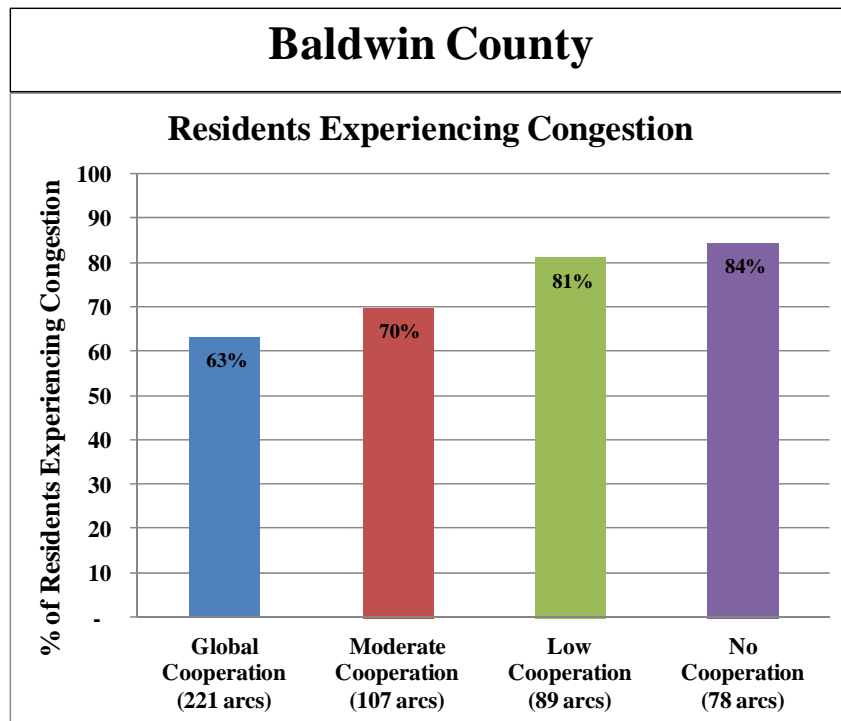

Figure 19. Baldwin County's proportion of residents that experience congestion and the number of congested arcs.
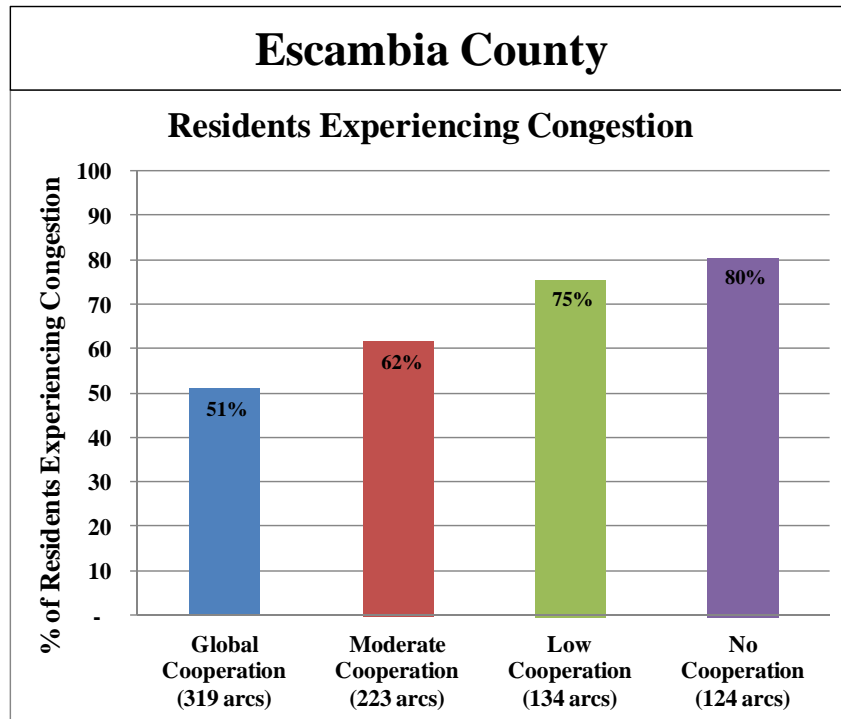
Figure 20. Escambia County proportion of residents that experience congestion and the number of congested arcs.
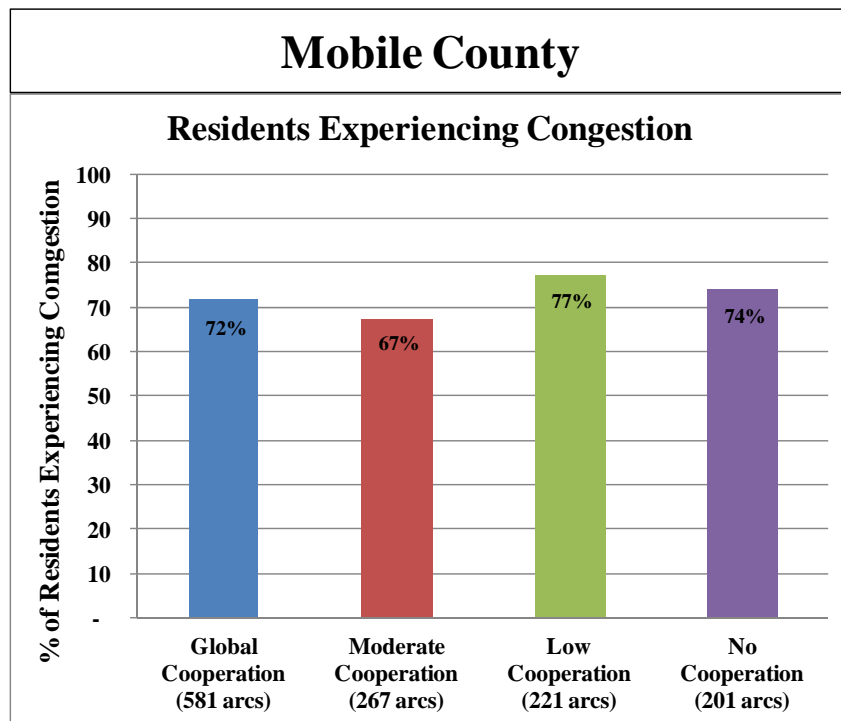

Figure 21. Mobile County proportion of residents that experience congestion and the number of congested arcs.

3. Benefits of Congestion on Clearing Times

A common focus of evacuation research is on dispensing evacuation notices in such a way as to minimize congestion (Li et al. 2010). In this section, we examine whether clearing time is worsened by congestion, or improved. We accomplish this by restricting MCF-CA to disallow congestion on all arcs in all time epochs, i.e., by setting $D_{ij1t} = 1$ for all (i,j,t). We denote the resulting clearing times as the *non-congested clearing times* and compare them to the *congested clearing times* generated in the previous section.

Figure 25 depicts congested and non-congested clearing times during a mass evacuation for all scenarios. Clearing times for the non-congested evacuations range between 22 and 130 hours, while clearing times for the congested evacuations range between 15 and 83 hours. By the fifth hour of evacuation, congestion helps evacuate 22–43% of residents, while only 16–28% of residents evacuate in the non-congested scenarios.

One might postulate that the 70–80% decrease in travel speed when going from under- to over-saturated conditions would sharply increase the congested clearing time. However, in over-saturated conditions over 50% more residents are able to start or continue evacuating in each time period, albeit at a slower speed. This finding is important because it reveals that while it is an annoyance, congestion alone does not prolong clearing times beyond those of non-congested evacuations. In fact, congestion improves evacuation clearing times by 20–36%. Therefore, even if state and local emergency managers were able to design a communication system that could produce 100% resident compliance and alleviate congestion, they would need to carefully weigh the impact on clearing time before implementing such a system.
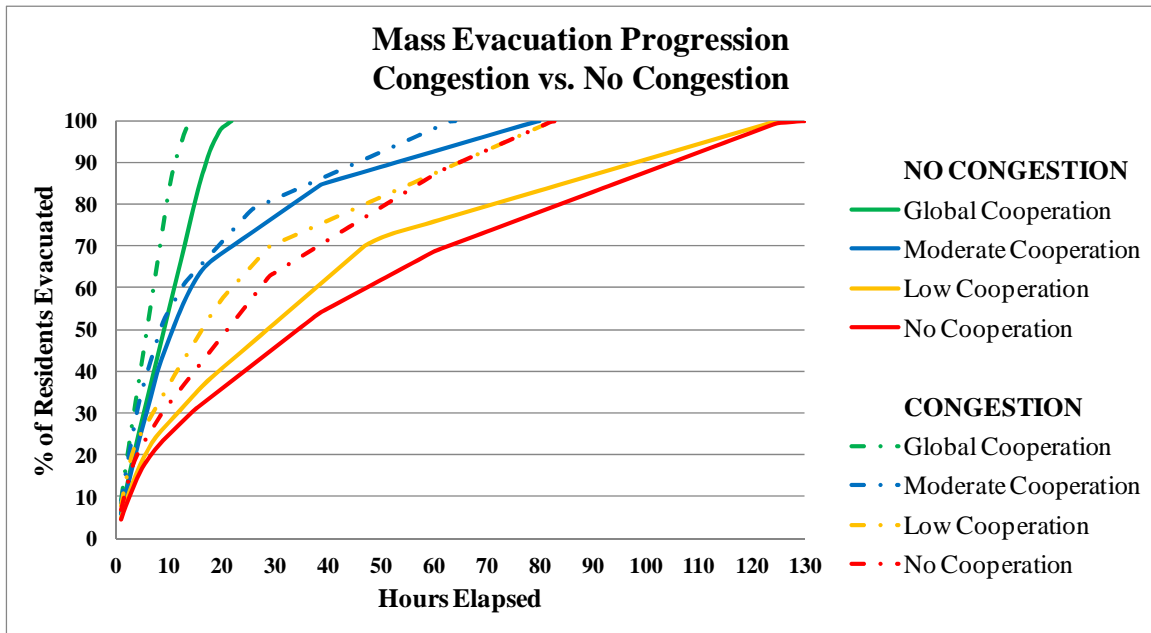
Figure 22.   Evacuation Progression for congested and non-congested mass evacuations.

VI. CONCLUSION AND FUTURE WORK

State and local emergency managers study evacuation clearing times in order to establish appropriate traffic control measures to mitigate the congestion that is likely to occur during the mass movement of residents. This thesis develops a new model for evacuations and uses this model to investigate evacuation clearing times on the multi-regional transportation network of Mobile County, AL, Baldwin County, AL, and Escambia County, FL. We create a spatial representation of this transportation network and compute the number of vehicles using this network using household vehicle availability data from the 2010 Census Survey.

We develop a multi-period integer linear program called the Minimum Cost Flow with Congestion Scheduling (MCF-CA) model. MCF-CA discretizes the nonlinear relationship between traffic flow, speed, and density. MCF-CA selects the lowest optimal congestion level that will maximize flows (i.e., throughput) in order to minimize the number of residents not evacuated for each time period.

We measure the impact of mass evacuation on county clearing times and explore the impact of congestion and routing on clearing times. Finally, we validate results using the 2010 clearing times generated by the U.S. Army Corps of Engineers, Mobile County District.

A. SUMMARY AND RECOMMENDATIONS

During evacuations, mass or otherwise, congestion is inevitable. In the best- and worst-case scenarios, more than 50% of residents will be congested at some point during the evacuation horizon. Nevertheless, this thesis demonstrates that congestion alone does not increase clearing times. Clearing times are shorter when residents are allowed to evacuate earlier when congestion is allowed versus later when congestion is not allowed. Congesting improves evacuation clearing time by 20–36% over not congesting because 50% more residents are able to start or continue evacuating during each time epoch.

However, MCF-CA does not consider secondary effects such as car accidents due to closer vehicle spacing during congestion. States and counties have many options to handle congestion, including improving roads, constructing new corridors, and using contra-flow. However, due to the growing rate of congestion in cities, new facilities would soon face the same congestion. Therefore, to keep the time-saving benefit of congesting, emergency managers might study traffic control measures that would help mitigate the secondary effects of congestion.

We observe that exit locations, not simply the number of exits, play a significant factor in estimating clearing times. Escambia County's clearing time during mass evacuations rise as much as threefold because a third of its exit points border Baldwin County. Having one set of exit points for both county and mass evacuations would decrease the difference in clearing times. Additionally, standardizing for both evacuation types would make it easier for residents to remember evacuation routing and procedures for any scenario.

Finally, we show that in scenarios with a higher percentage of residents following their directed shortest path routes, clearing times lengthen by as much as two to four times. Residents must sometimes be encouraged to use exits that are distant in order to ensure timely evacuation of all residents. Thus, intelligent routing decisions by residents are the key to ensuring an efficient evacuation. While it is not realistic to expect that residents will cooperate as a system to minimize clearing times, it is equally unrealistic to assume that residents will stay on a designated route throughout the evacuation horizon. As a compromise, MCF-CA could be implemented in future studies to analyze the effect of varying the amount of residents who decide not to follow the designated route to specified destination points.

B. FUTURE WORK

The MCF-CA model has enough flexibility to be applied on all levels of analysis (microscopic, mesoscopic, and macroscopic). Some areas of possible research are:

- Determining the impact of individual route-change decisions when faced with traffic congestion,

- Exploring the effect of individual household destination decisions on traffic congestion,

- Analyzing the effect of varying the number of individuals who follow designated routes to specified destinations, and

- Designing a community controlled departure system that decides route and departure time jointly and accounts for disaster uncertainty.

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APPENDIX. ADDITIONAL GRAPHS

C.   CONGESTION DURING SUB-OPTIMAL ROUTING

Figures 23 and 24 show Baldwin County and Escambia County residents' evacuation progression and the percent of roads utilized in each epoch that are road congested, respectively.
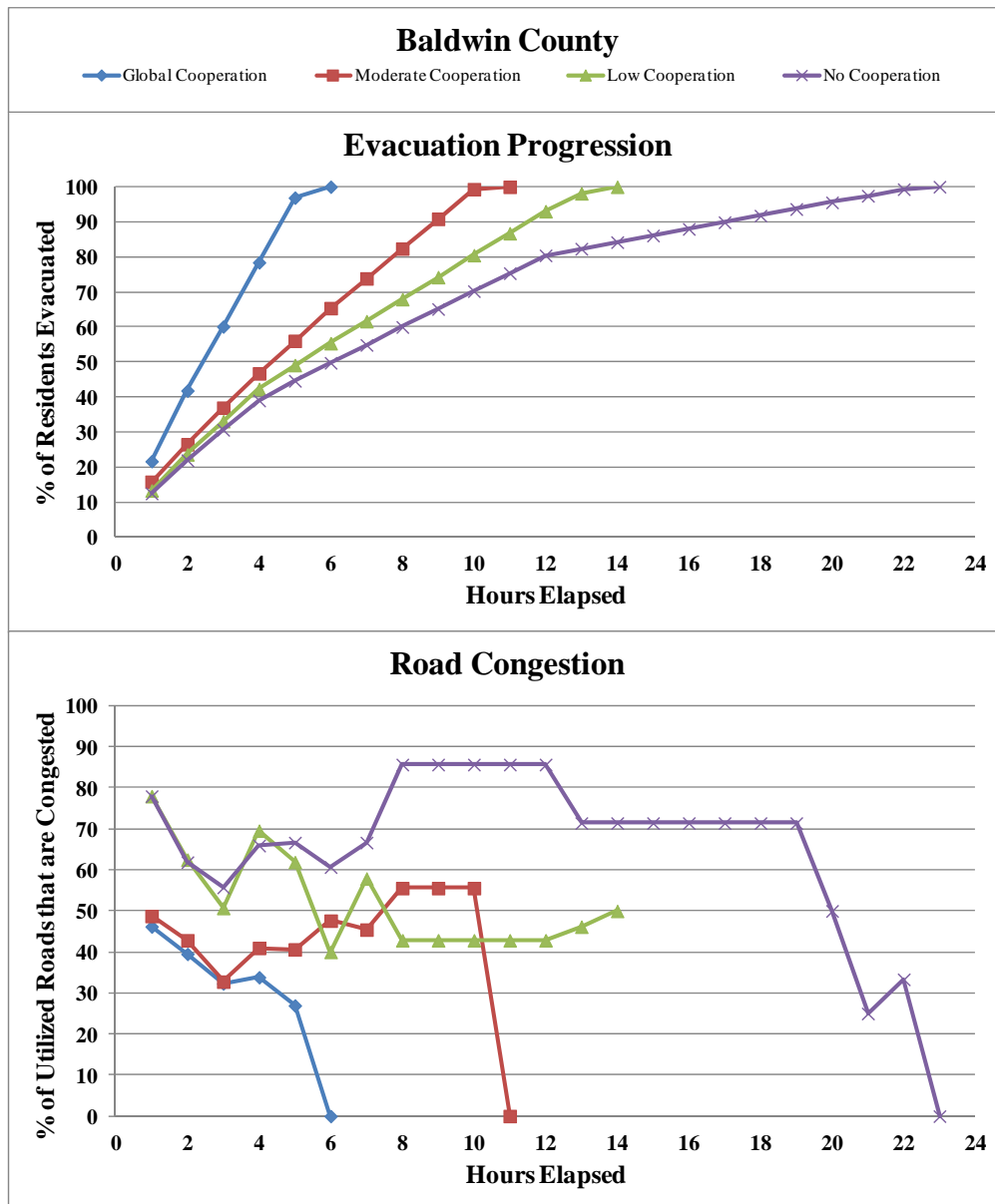

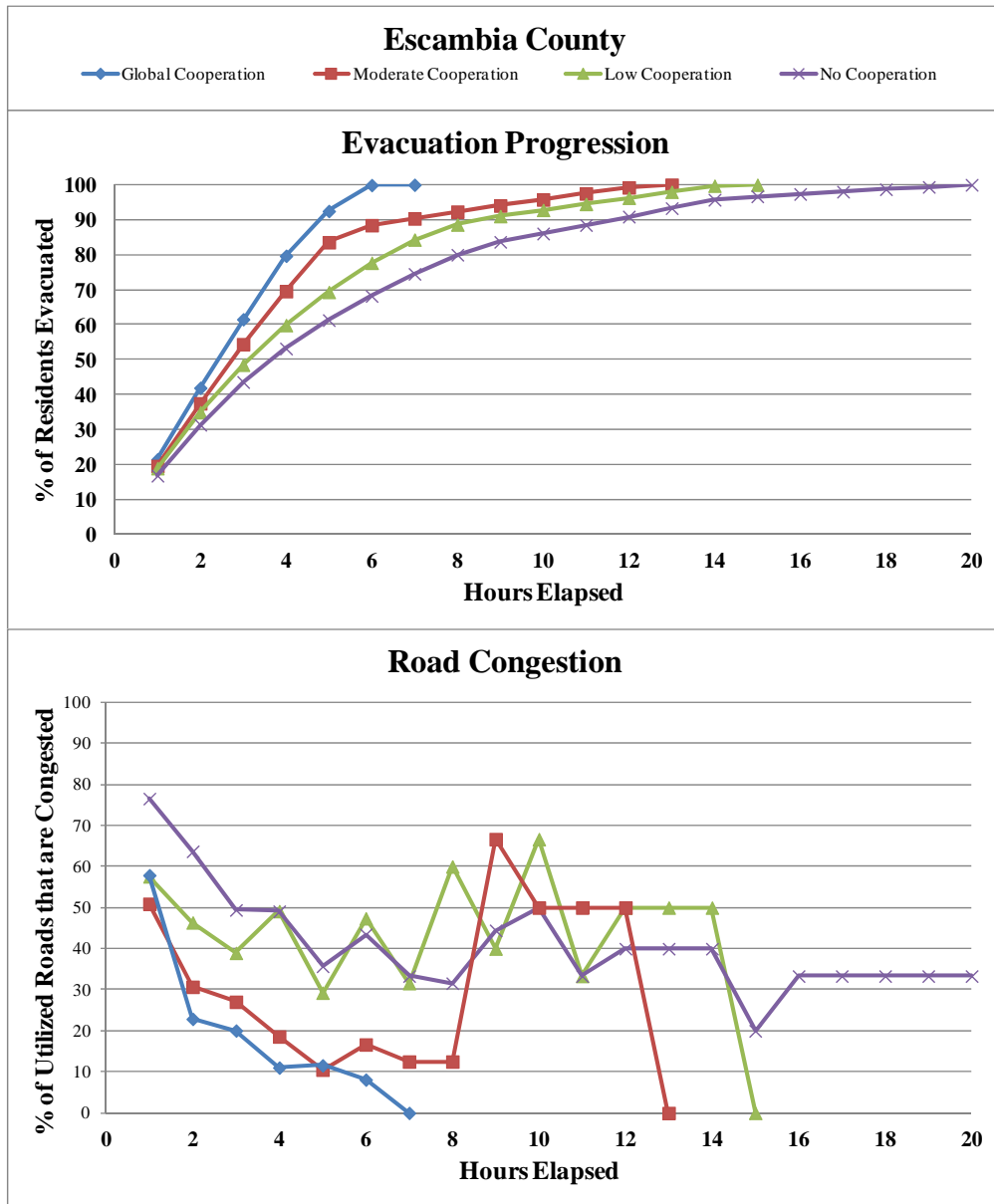Figure 23.   Baldwin County evacuation progression and road congestions.

Figure 24.   Escambia County evacuation progression and road congestions.

LIST OF REFERENCES

Ahuja, R. K., T. L. Magnanti, and J. B. Orlin. *Network Flows.* Upper Saddle River, New Jersey: Prentice Hall, 1993.

Akçelik, R. *Speed-Flow Models for Uninterrupted Traffic Facilities.* Greythorn Victoria, Australia: Akçelik & Associates Pty Ltd, 2003.

Arnott, R. A., A. de Palma, and R. Lindsey. "Information and Time-of-Usage Decisions in the Bottleneck Model with Stochastic Capacity and Demand." *European Economic Review* 43, no. 3 (1999): 525–548.

Brown, G., and T. Halwachs. *U.S. Road Data Base for Network Modeling.* Monterey, CA: (private communication), August 21, 2012.

Cambridge Systematics, Inc. *Traffic Congestion and Reliability: Linking Solutions to Problems.* Washington, DC: Federal Highway Administration, 2004.

———. *Traffic Congestion and Reliability: Trends and Advanced Strategies for Congestion Mitigation.* Washington, DC: Federal Highway Administration, 2005.

Cheng, G., C. G. Wilmot, and E. J. Baker. "A Destination Choice Model for Hurricane Evacuation." *Transportation Research Board 2008 Annual Meeting.* Washington, DC: Transportation Research Board, 2008.

Crews, J. C. *Determining Optimal Evacuation Decision Policies for Disasters,* M.S. Thesis in Operations Research. Monterey, CA: Naval Postgraduate School, 2012.

Czajkowski, J. "Is It Time to Go yet? Understanding Household Hurricane Evacuation Decisions from a Dynamic Perspective." *Natural Hazards Review* (American Society of Engineers), 2011: 1–13.

DesRoches, R. *Hurricane Katrina: Performance of Transportation Systems.* Reston, Virginia: American Society of Civil Engineers, 2006.

Dombroski, M., B. Fischhoff, and P. Fischbeck. "Predicting Emergency Evacuation and Sheltering Behavior: A Structured Analytical Approach." *Risk Analysis* 26, no. 6 (2006): 1675–1688.

Federal Emergency Management Agency. *National Response Framework.* January 2008. http://www.fema.gov/national-response-framework (accessed March 05, 2013).

———. "State and Local Guide (SLG) 101: Guide for All-Hazard Emergency Operations Planning." *Guide for All-Hazard Emergency Operations Planning.* September 1996. http://www.fema.gov/pdf/plan/slg101.pdf (accessed March 05, 2013).

Federal Highway Administration. *Catastrophic Hurricane Evacuation Plan Evaluation: A Report to Congress.* Washington, DC: Federal Highway Administration, 2006.

Federal Highway Administration. *Highway Evacuations in Selected Metropolitan Areas: Assessment of Impediments.* Washington, DC: Federal Highway Administration, 2010.

Fosgerau, M. "Congestion costs in bottleneck equilibrium with stochastic capacity and demand." *Munich Personal RePEc Archive.* August 14, 2008. http://mpra.ub.uni-muenchen.de/10040/ (accessed July 15, 2012).

Galveston District, U.S. Army Corps of Engineers. *State of Texas: Post Storm Assessment - Hurricane Ike.* Galveston, Texas: Federal Emergency Management Agency, 2010.

Google, Inc. *Google Earth.* 2012.

Hall, F. L. "Traffic Stream Characteristics." In *Traffic Flow Theory*, Chapter 2. Washington, DC: Federal Highway Admnisitration, 1992.

Highway Research Board. *Highway Capacity Manual.* HRB Special Report 87, Washington, DC: Highway Research Board, 1965.

Langford, W. P. *A Space-Time Flow Optimization Model for Neighborhood Evacuations, M.S. Thesis in Operations Research.* Monterey, CA: Naval Postgraduate School, 2010.

Li, C., F. Wang, X. Zhou, and X. Chen. "Simulation Study of Operational Strategies for Congestion Mitigation During Emergency Evacuation." *National Evacuation Conference.* New Orleans, LA: National Evacuation Conference, 2010.

Mobile District, U.S. Army Corps of Engineers. *State of Alabama Post Storm Assessment: Hurricanes Gustav and Ike.* Mobile, Alabama: Federal Emergency Management Agency, 2009.

———. *Transportation Analysis for Alabama Hurricane Evacuations.* Mobile, Alabama: Federal Emergency Management Agency, 2010.

Saffir-Simpson Team. "The Saffir-Simpson Hurricane Wind Scale." *Saffir-Simpson Hurricane Wind Scale.* February 1, 2012. http://www.nhc.noaa.gov/pdf/sshws_2012rev.pdf (accessed May 9, 2012).

Sheffi, Y., H. Mahmassani, and W. B. Powell. "Evacuation Studies For Nuclear Power Plant Sites: A New Challenge For Transportation Engineers." *Institute of Transportation Engineers*, 1981: 25–28.

Singh, R. "Improved Speed-Flow Relationships: Application to Transportation Planning Models." *Improved Speed-Flow Relationships: Application to Transportation Planning Models.* March 1995. http://www.mtc.ca.gov/maps_and_data/datamart/research/boston1.htm (accessed January 15, 2013).

Transportation Research Board. *HCM 2010 : Highway Capacity Manual.* Washington, DC: Transportation Research Board, 2010.

U.S. Army Corps of Engineers. *Northwest Florida Hurricane Evacuation Study Technical Data Report.* Washington, DC: Federal Emergency Management Agency, 1999.

Vickrey, W. S. "Congestion Theory and Transport Investment." *American Economic Review* 59, no. 2 (May 1969): 251–260.

Wardrop, J. G. "Some Theoretical Aspects of Road Traffic Research." *Institute of Civil Engineers* 1, no. 3 (June 1952): 325–362.

Yuhas, T. C. *Escape from the Delta: Preparations and Evacuations for Catastrophic Flooding in California Emergency Management Agency Region IV,* M.S. Thesis in Operations Research. Monterey, CA: Naval Postgraduate School, 2011.

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